Transparent insulation materials: an overview on past, present and future developments

Paneri, A.; Wong, I.L.; Burek, S.

Published in:
Solar Energy

DOI:
10.1016/j.solener.2019.03.091

Publication date:
2019

Document Version
Author accepted manuscript

Citation for published version (Harvard):
Paneri, A, Wong, IL & Burek, S 2019, 'Transparent insulation materials: an overview on past, present and future developments', *Solar Energy*, vol. 184, pp. 59-83. https://doi.org/10.1016/j.solener.2019.03.091

Transparent Insulation Materials: An overview on past, present and future developments

A. Paneri[1], I. L. Wong[2] and S. Burek[2]

[1]Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, TR10 9FE, United Kingdom

[2]School of Computing, Engineering and Built Environment, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, Lanarkshire G4 0BA, United Kingdom

Email: anshulpaneri@gmail.com (A Paneri); IngLiang.Wong@gcu.ac.uk, xijiayu@hotmail.com (IL Wong); S.Burek@gcu.ac.uk (S Burek)

Abstract

Transparent Insulation (TI) systems are regarded as one of the most promising technologies for providing thermal insulation along with transmission of solar energy. TI systems have a wide range of applications in energy conservation and harnessing solar energy. This paper provides an overview of TI systems and TI materials (TIM), by characterising TI systems on the basis of geometry, material used and general heat losses in these geometrical layouts. Evolution of TI applications is presented with the introduction of new materials. Two new types of TIM (polypropylene and cellulose acetate) are reported in this paper in contrast to previous reviews on TIM. A systematic survey of past literature was carried out to present latest research works and development on TI geometrical layouts and applications. An explicit study of TIM and TI system manufacturers has been carried out to show existing trends in TI applications and geometry. In the last decade, aerogels are most frequently used as TIM for providing insulation and daylighting in buildings. It is concluded that in existing TIM technologies, TI systems incorporating aerogel have the lowest thermal transmittance (U-value) and better solar transmittance (g-value) at lower thickness compared with TI systems incorporating other types of TIM. This paper highlights the availability of TIM geometry with desirable applications and TI systems for energy conservation.

Keywords –TI (Transparent / Translucent insulation); TIM (Transparent / Translucent Insulation Material); thermal transmittance (U-value); solar energy transmittance (g-value); aerogel

---

Contents

---

1. Introduction

Efforts in harnessing solar energy have increased steadily in the last two centuries, which have resulted in continuous improvement in technologies to capture solar heat energy efficiently. A transparent insulation material (TIM) is an advanced material which can capture and efficiently retain solar heat energy by minimising heat losses. It enhances insulation ability by reducing the flow of heat energy within small air gaps or evacuated spaces in low thermal conductivity materials. The TIMs ability to reduce thermal loss and to provide solar transmission varies depending on operating temperature, geometrical structure and material types (Tabor, 1969). Thus, to characterise TIM for different applications, thermal transmittance (U-value) and solar transmittance (g-value) are two essential parameters (Kaushika and Sumathy, 2003). Solar transmittance of more than 50% and thermal transmittance lower than 1 W/(m^2K) provide TIM with a wide range of applications, such as solar heating and daylighting (Wong et al., 2007). This review paper presents past and current research undertaken on transparent insulation (TI) technology, including applications, current trends and scope for future development. Additionally, it presents the current TIM and transparent insulation (TI) systems available in the market with their specifications.

2. TI Classification, Materials and Heat losses

A TI system can be defined as a structural system which includes TIM. TIM can be classified by the manufacturing process, material type or geometrical structure, and has g-values depending on thickness (see appendix 1 and 2). TIM can be classified into four generic types (Dowson, 2012; Kaushika and Sumathy, 2003; Wittwer and Platzer, 1999; Wong et al., 2007), according to geometry. Figure 1 illustrates various types of TIM geometries with absorbers, heat losses associated with these geometries and materials available for use in these geometries.

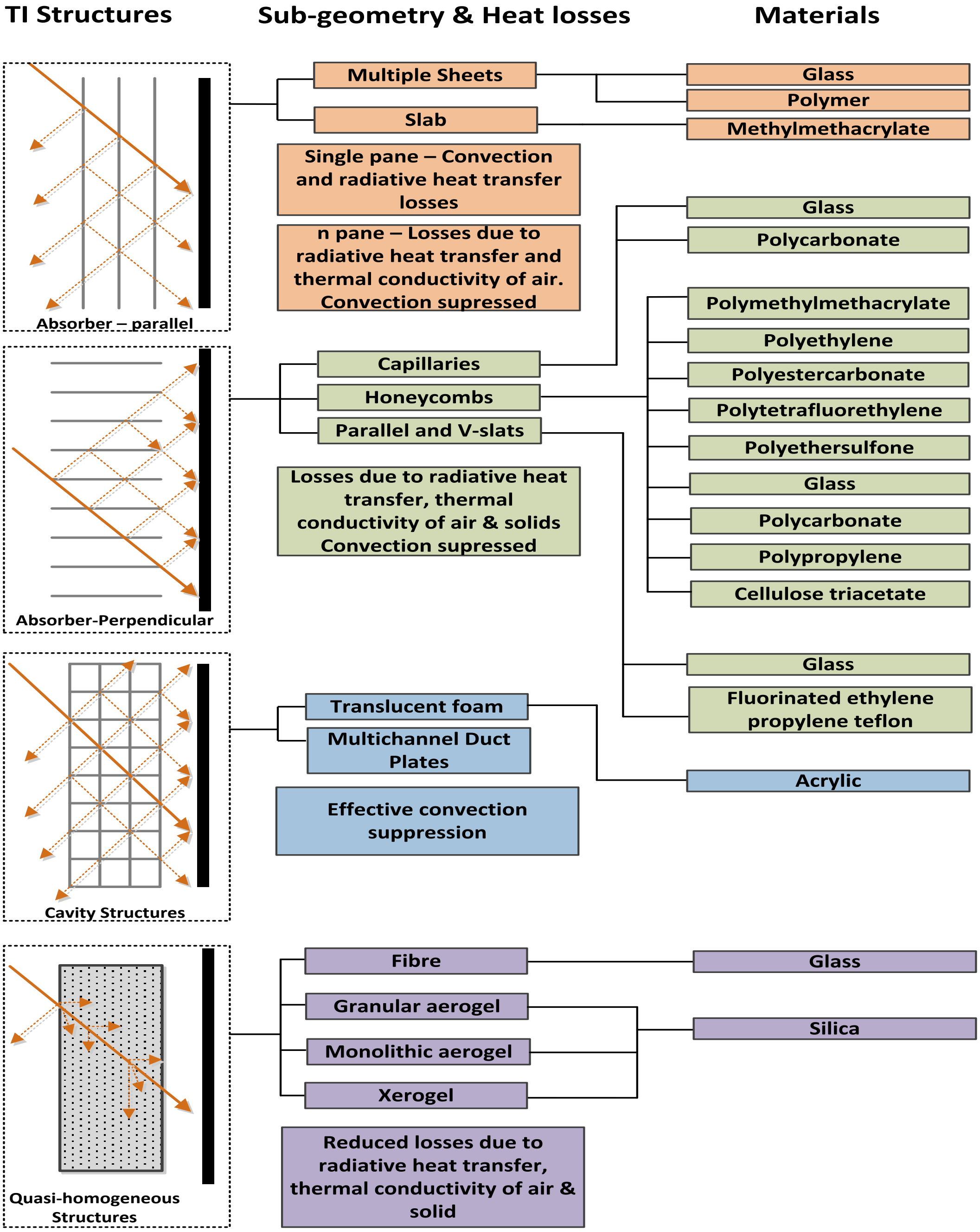

Figure 1 TIM geometry types with material and heat losses associated (Dowson, 2012; Wittwer and Platzer, 1999; Wong et al., 2007)

In the absorber-parallel structure, sheets or slabs are placed parallel to the absorber as a cover. Heat losses are generally due to convection and radiative heat transfer. Increasing the number of parallel sheets can further reduce these losses, but this will result in a reduction of solar gain due to increased optical reflections. Thus, it is not possible for this kind of structure to have low heat loss and high solar transmission at the same time. Absorber-perpendicular structures have minimum reflection losses along with reduced heat losses. These consist of honeycombs, capillaries or parallel slat arrays placed perpendicular to the absorber to provide a forward reflection of incoming radiation. In this type of structure, heat loss through convection can be efficiently suppressed with an appropriate aspect ratio. It has been used in a wide range of TI applications, notably in solar collectors. The third generic type of TIM is cavity structure which is obtained by combining absorber-parallel and absorber-perpendicular structures. Translucent foam and multichannel duct sheets are examples of cavity type structures. These structures can suppress convective heat loss efficiently but have high reflection loss resulting in reduced transmittance similar to a multiple film cover. The last type of TIM is quasi-homogeneous structure, which has a homogeneous distribution of air in the material. Glass fibre, aerogel, xerogel are quasi-homogeneous types of structure. They have very low reflectance, while transmission losses are due to scattering and absorption of incoming radiation. In quasi-homogeneous structure, heat losses by radiation and conduction through the air are very low, and heat conduction through the solid is also very low (Kaushika and Sumathy, 2003; Wittwer and Platzer, 1999; Wong et al., 2007). It should be noted that there are also transitional materials which cannot be classified in one single generic type shown in Figure 1, such as, folded or V-corrugated films, slanted cell honeycomb structures (Wittwer and Platzer, 1999).

A comparative study by Wittwer and Platzer (1999) provides some clear vision on which type of geometrical structure provides lowest U-values. The study shows a U-value of 6 W/(m^2K) in an absorber parallel configuration with a single pane of glass and absorber. When the number of glass panes is increased to three in this configuration, the U- value is reduced to 2 W/(m^2K). If honeycomb is used (absorber-perpendicular configuration), the U-value can be reduced further to 0.90 W/(m^2K). The lowest U-value of 0.20 W/(m^2K) can be achieved using aerogel a quasi-homogenous structure (Wittwer and Platzer, 1999).

All configurations presented in figure 1 have some limitations which make them only suitable for specific solar applications. Among all these configurations, an absorber-perpendicular structure using honeycomb cellular arrays is the most documented geometrical configuration of TIM (Kaushika and Sumathy, 2003; Wong et al., 2007).

3. TI applications & materials

TIM is used for collecting solar energy and providing insulation to avoid heat losses so that all TIMs can be termed as solar collectors. However, on the basis of utilisation of this solar energy, TIM applications can be divided into two major categories:

1. TI system for solar collectors: Solar ponds, solar water heaters, integrated storage collectors etc.
2. TI system for buildings: Facades, Roof lights, glazings, skylights, greenhouses (horticulture), etc

The first ever recorded TIM research is by V.B. Veinberg in the year 1928 on honeycomb structures for thermal insulation of the surfaces of solar installations (Grilikhes, 2007). He presented a Flat Plate Collector (FPC) with a honeycomb made of specially treated paper placed between the glass cover and absorber to reduce heat losses by radiation and convection (Grilikhes, 2007; Tabor, 1969; Wong et al., 2007). His work was published later in 1959, in the monograph “Optics in solar energy utilisation systems” (Grilikhes, 2007). The next significant work on TIM was published in 1961 at United Nations conference on new sources of energy, by Francia. The study demonstrated the use of long glass tube honeycomb structure in a solar collector to achieve high operating temperatures for modern heat engines to reduce re-radiation of collected solar radiation (Francia, 1963). It was clear that with the TIM available at the time, radiative heat losses could be reduced significantly and the remaining convective and conductive heat losses were the next to be addressed. In 1965, Hollands conducted a theoretical study on the suppression of convective heat losses using thin-walled honeycomb structures for FPCs operating at low temperatures (Hollands, 1965). In 1968, Pellette and colleagues conducted experiments on evacuated cylinder collectors with hexel honeycomb core made of glass reinforced plastic, which demonstrated an operating temperature of 204 °C and capable of operating at higher temperatures (Pellette et al., 1968). In 1969, Tabor demonstrated experimentally that, when the cell size of honeycomb was reduced to 1cm or less, convection heat transfer could be suppressed. He concluded that despite glass tube honeycombs being expensive, they are ideal for concentrating solar collectors. Plastic honeycombs can be cost-effective in FPC, but there was no availability of plastic with desired optical and thermal characteristics (Tabor, 1969). The absence of suitable material compelled researchers to use different materials for developing efficient TI systems for solar collectors. In 1976, Marshall and colleagues (Marshall et al., 1976) had addressed this problem by developing a thin-film transparent plastic honeycomb. Four different plastics: Lexan, Mylar, Tedlar and Kapton were used to manufacture FPC honeycombs with operating temperatures between 81 °C and 121 °C. Experimental studies showed that it is possible to get efficiencies higher than 50% with honeycomb collectors for temperatures up to 109 °C. Marshall et al. (1976) concluded that Lexan and Mylar honeycombs have the highest efficiency which can reduce collector costs based on the amount of energy collected (Marshall et al., 1976). Another experimental study on the solar transmittance of convection suppression devices was presented by Symons, where different design geometries including honeycombs made from FEP Teflon 1 film and tubular glass honeycombs have been included (Symons, 1982).

With the addition of new materials as TIM, applications of TIM started expanding. In 1980, TIM was introduced in building application as transparent and translucent thermal insulation material for solar heat gain and daylighting. Rubin and Lampert in 1983 studied the use of silica aerogels for windows and concluded that theoretically aerogel windows could have lower U-value than multiple glass window of equal g-value. According to them, further thermal conductivity reduction in aerogel window is possible by filling aerogel window with a gas having lower thermal conductivity or evacuating aerogel windows (Rubin and Lampert, 1983). Stahl et al. (1984), conducted a study of different geometrical arrangements of TIM, confirming that the heat transfer coefficient for aerogel is lower than the capillary structure they had tested. However, they considered it impractical to use aerogels because of the technical challenges and high cost of production (Stahl et al., 1984). In 1984, Goetzberger et al. conducted an experimental study showing efficient use of TI systems for heated walls with PMMA (poly-methyl methacrylate – acrylic) foam and capillaries as TIM (Goetzberger et al., 1984). In 1987, An experimental study was undertaken on the usage of TIM in buildings and solar collectors, where Goetzberger (Goetzberger, 1987) concluded that aerogels could be applied to buildings especially in windows, but it was not practically feasible due to high material cost. He also concluded that plastic TIMs have limitations on their operating temperatures. Thus for solar collectors, TIM must be chosen on the basis of their desired operating temperatures. For example, aerogel pellets can be used for collectors that require high operating temperatures (Goetzberger, 1987). With the availability of additional materials that can be used as TIM, it was essential to categorise them and develop a theoretical model for their properties. In 1987, Platzer categorised TIM into four different types on the basis of geometry and presented theoretical models to calculate solar transmittance for different TIM, and then validated them experimentally (Platzer, 1987). Similarly, Antonio Pfluger in 1987 presented thermal conductivity of TIM with different geometries and concluded that minimum thermal conductivity could be achieved with a homogeneous distribution of material, such as silica aerogels (Pflüger, 1987). In 1992, Platzer carried out studies on honeycomb structures using different TIM for optical and thermal properties (Platzer, 1992a, 1992b, 1992c). During the same year, modelling of FPC using monolithic silica aerogel presented by Nordgaard and Beckman showed a decrease in solar transmittance is compensated by a reduction in thermal losses (Nordgaard and Beckman, 1992).

Another example of TIM applications is the use of TI systems for integrated collector storage, which has been widely discussed (Avanti et al., 1996; Goetzberger, 1987; Kaushika and Reddy, 1999; Kaushika and Sharma, 1994). In 1996, Platzer and Goetzberger carried out a study on advancement in TI and presented TI system manufacturers, system technology and maturity of TI systems in the market. According to Platzer and Goetzberger, OKALUX Kapillarglass GmbH (Marktheidenfeld, Germany) and AREL energy Ltd. (Yavne, Israel) were the two manufacturers dominant in this market during 1990's (Platzer and Goetzberger, 1996). In 1998, Platzer studied advancements in TI systems and barriers associated with the commercialisation of these systems. He provided a classification of TI in the market by their geometry and presented projects with TI-application (Platzer, 1998). Later on in 1999 Platzer along with Wittwer presented an overview on generic types of TIM, available commercial TI systems, demonstration projects, future potential of TI systems and finally their market penetration during the time of the study (Wittwer and Platzer, 1999). Hollands and colleagues in 2003 presented a thermal model for a new type of honeycomb configuration, by investigating honeycombs in greenhouses for energy conservation (Hum et al., 2004). Kaushika and Sumathy (2003) presented a review of TIM applications, their classification, cost trends and fabrication of systems (Kaushika and Sumathy, 2003). In 2007, Wong et al., presented a detailed material diagram of TIM, categorising materials used on the basis of TIM geometry. They also explained barriers to development and implementation of TI systems and presented a payback period calculation for TI system in building applications (Wong et al., 2007).

Advances in research and technological development have driven TIM manufacturers to produce TIM with low-cost materials with better optical and thermal properties. Wallner et al. (2005) established a fundamental understanding of the physical relationship between material structure and solar optical and infrared optical properties of polymeric TIM (Wallner et al., 2005a, 2005b).

Figure 2 demonstrates various TIM applications discussed to date. The immense pressure to achieve zero carbon building goal in the EU and USA has resulted in increasing research activities in TIM for building applications. Silica aerogels have shown significant potential as TIM, but due to the complexity and high cost of manufacturing, it had not been commercialised on a large scale until the 1990s. However, this has now changed as aerogel is available at affordable price for building applications (Huang, 2012), which has made it possible to commercialise different types of TI systems.

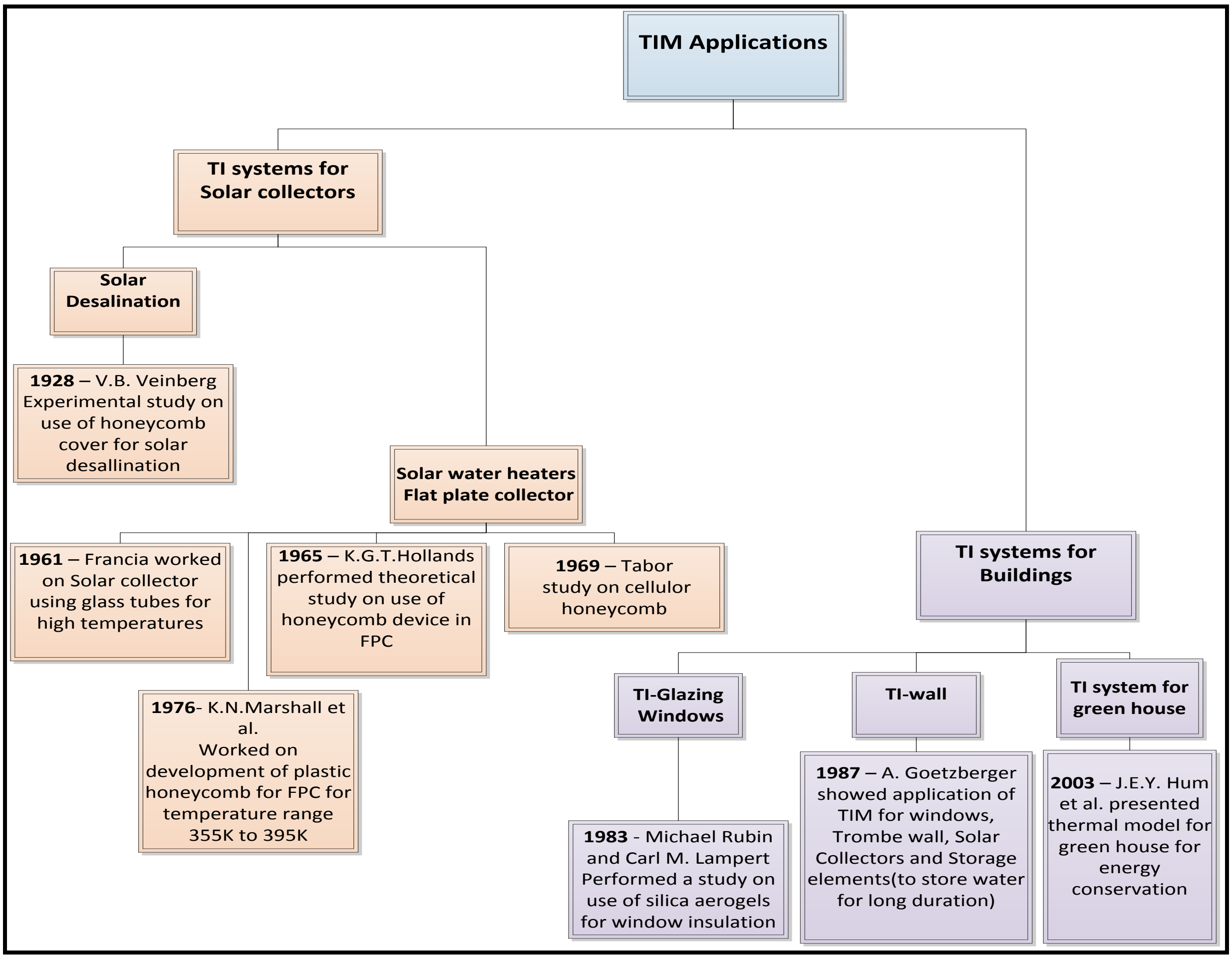

Figure 2 Tree diagram representing growth of TIM applications

4. Analysis of Research on TI applications and geometry

With the availability of a wide range of TIM, it is possible to manufacture TI systems for different applications. However not every TIM geometry is suitable for all types of TIM applications because of manufacturing costs, working temperature of the TIM, importance of high g-value and low U-value in the application. The aim of this paper is to review different TIM geometries preferred by researchers for different applications. A total 86 publications (Listed in appendix 4) on TIM geometry and applications are organised into two groups based on their year of publication to present the preferred TIM geometry for a particular application:

1. Papers published from the start of TI research (1928) until December 1999
2. Papers published from 2000 to 2017.

This arrangement of research papers presents a clear view of the advancement of TIM technology with time. It also provides knowledge on TI applications with technological development. Similarly, it provides excellent

TIM geometrical layout for TI applications with time. The TIM applications and geometry are categorised as shown in Table 1:

Table 1 TI Applications and geometries for the analysis

	TI applications:	TI geometry:
1	Solar pond	Absorber - parallel
2	Solar Collectors	Absorber - perpendicular
3	ICS – Integrated collector storage	Quasi-Homogeneous
4	TIM – general	Cavity
5	Building	
6	Review on TIM	
7	Greenhouses	

4.1 Research Trends from 1900 to 1999

Figures 3 and 4 present initial development in TI applications and the most widely available TI geometries in the early 20th century. As shown in the figures, absorber-perpendicular structures are the most widely reported type of TI geometrical layout, and TIM was mostly used in solar collectors.

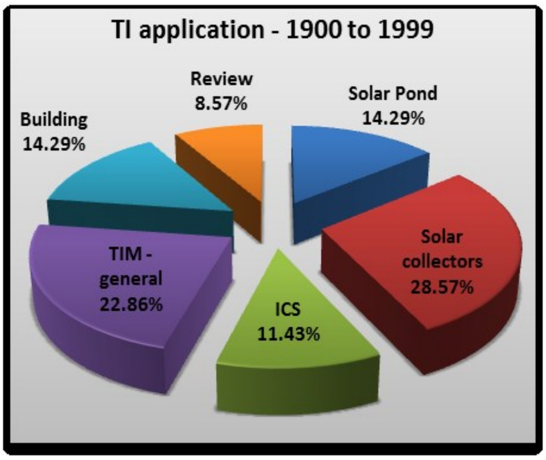

Figure 3 TI applications percentage share

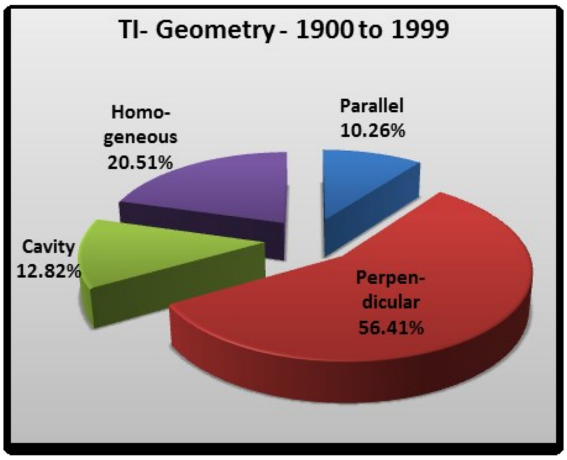

Figure 4 TI geometries percentage share

Most previous studies were on absorber-perpendicular structures because they have better insulating properties with lower cost and reduced TI-system thickness compared with absorber-parallel structures. Although studies on quasi-homogeneous structures have started from 1980’s, their high cost and manufacturing difficulties were the reasons for fewer research activities on quasi-homogeneous and cavity structures. Many experimental and theoretical studies undertaken, show that quasi-homogenous structures have lower U-values than other geometrical structures, but cost and energy conservation determine the TI application of these geometries (Duer and Svendsen, 1998; Goetzberger, 1987; Goetzberger et al., 1984; Nordgaard and Beckman, 1992; Pflüger, 1987; Platzer, 1987; Rubin and Lampert, 1983; Stahl et al., 1984; Wittwer, 1994).

Solar collectors can be used in different applications, such as water and air heating, desalination and integrated collector storage. In these applications, absorber-perpendicular structures were most widely investigated and used as convection suppression devices. The high cost of quasi-homogeneous structures did not justify their selection for collectors. In figure 3, TIM general represents research performed on the development of existing and new materials as TIM. These research studies contribute to the understanding of types of heat losses TIM can suppress, and the amount of solar energy TIM can transmit for further development of the technology. TI for building applications is relatively new compared to solar collectors, but from early 1980's, researchers started to show interest in these types of applications. In TI building applications, homogeneous geometry is preferred due to lower U-value and better g-value. For example, Duer and Svendsen (1998) demonstrated an evacuated aerogel double glazed unit with a thickness of 28mm could have a U-value of 0.47 W/(m^2K) and a g-value of 0.79 (Duer and Svendsen, 1998). However, high cost and manufacturing difficulties made it impractical to introduce TI systems with homogeneous structure in the market for TI building applications. Notable studies (Goetzberger, 1987; Goetzberger et al., 1984; Wittwer, 1994) on TI building applications with the cavity and absorber-perpendicular geometries have been reported. For example, Goetzberger (1984) demonstrated the use of PMMA foam and capillary structure for building facades in Freiburg, Germany (Goetzberger et al., 1984).

4.2 Research Trends from 2000 to 2017

During the late 1990's, research undertaken on TIM has shown the benefits of TI systems in energy conservation, which have resulted in increasing research activities in the last decade. Figures 5 and 6 show pie charts for research conducted on different TI applications and geometrical layout of TI systems from 2000 to 2017. TIMs are most frequently applied to buildings since 2000 because of their capability to provide insulation and daylight. Similarly, in the geometrical layout of TI systems, works on homogeneous geometrical structures have increased due to a reduction in manufacturing cost. Most of the homogeneous geometrical structures investigated are for building applications as these geometrical structures can provide lower U-value with better g-value. For example, Buratti and colleagues concluded that an aerogel double glazed unit of 23mm thickness can have a U-value of 1 W/(m^2K) and a g-value of 0.57 (Buratti et al., 2017).

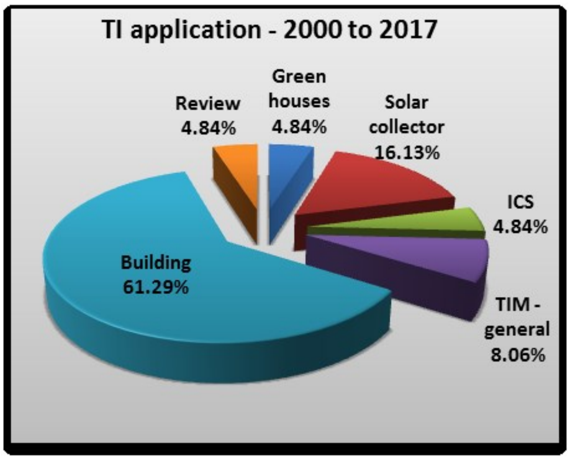

Figure 5 TI application percentage share

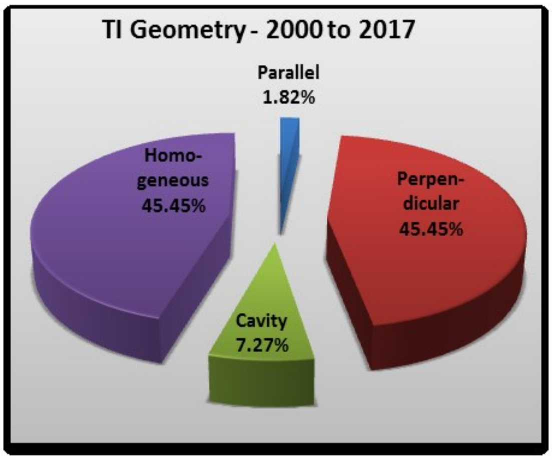

Figure 6 TI geometry percentage share

Absorber-perpendicular structures have been researched primarily for solar collectors and building applications due to their low cost. Today, there are several TI manufacturers, producing TI systems with quasi-homogeneous and absorber-perpendicular geometry for building applications.

5. Production

TIM production has not been straightforward and cost-efficient in the past, but with advances in technology, it has become possible to produce TI systems with U-values of lower than 1 W/(m^{2}K) and solar transmission of higher than 50%, as shown in Appendices 1 and 2. Currently, there are many companies which are producing TIM and TI systems for building and solar collector applications. This increase in production evidently demonstrates growth in market share of TIM with a reduction in cost.

5.1 TIM manufacturers

Current TIM manufacturers, types of materials used and geometrical layout of TIM available in the market are summarised in Table 2. Insulating glazing units an absorber parallel TIM are excluded from this list, considering their high cost to achieve low U-value and maintenance in comparison to other TIM structures. Single glazings and double glazings with vacuum or gas fillings are very common and readily available insulated glazing units, but these systems are not energy efficient compared with more advanced structures. Further reducing U-value in these systems requires multiple panes and expensive coatings, leading to increased thickness and weight of the unit compared with other TIMs.

In the existing market, absorber-perpendicular, cavity and quasi-homogenous TIMs are available for different applications, as listed in Table 2. Some transitional geometrical TIMs are also available in the market such as slanted honeycomb cells on absorber. This arrangement provides TIMs with intermediate geometry between an absorber-perpendicular and cavity structure. Most of the manufacturers currently use polycarbonate and silica aerogels to produce TIMs, but other materials are also available. For example, Wacotech produces transparent honeycomb with 9mm cell diameter from cellulose triacetate material. They also manufacture spun glass fibres with low light transmittance but better thermal insulation ("wacotech," n.d.). OKALUX, a German manufacturer, also uses PMMA to produce capillaries which are assembled in a honeycomb geometrical structure to create a TIM ("OKALUX GmbH," n.d.). GAP solutions is an Austrian company which manufactures honeycomb panels from cardboard in a range of colour from black to grey. This cardboard type of honeycomb TIM acts as shading to provide sun protection during summer when the sun is at higher altitude. During winter, when the sun is at lower altitude sunlight can penetrate deep into the cardboard honeycomb to provide solar gain ("GAP: GAP Solutions GmbH," n.d.). In other development, Advanced Glazings manufactures thin honeycomb films from Polypropylene plastic ("Solera | Architectural Daylighting - AdvancedGlazings.com," n.d.). CABOT corp, a dominant particulate silica aerogel manufacturer from the USA, supplies granular aerogel particles to many companies to produce TI systems for building applications ("Home," n.d.). In recent years, new aerogel manufacturers have emerged in the market. For example: Green Earth Aerogel Technologies (GEAT) from Spain has started to manufacture silica aerogels from agricultural waste, using rice husk as raw material ("Products of GEAT," n.d.); ENERSENS from France manufactures silica aerogel particles with a brand name Kwark white ("Enersens Aerogels | High Performance Silica Aerogel," n.d.), and JIOS Aerogel Limited from South Korea manufactures silica aerogel powders for use in light diffusion and insulating systems ("JIOS Aerogel » JIOS AeroVa® Aerogel Powder," n.d.). Some products are not shown on manufacturers' websites, such as Nano High-Tech Co. Ltd aerogel daylighting panels ("Nano Tech Co., Ltd. - aerogel, aerogel blanket, insulation Panel, aerogel felt, thermal insulation," n.d.), whereas Sto Groups external wall insulation system 'StoSolar' is marketed only on their Netherlands website ("StoSolar: tot 95% rendement uit zonne-energie | Sto," n.d.). In addition, Airglass AB, a Swedish company which had involved in different research projects on monolithic silica aerogel panels, have no updated information on their products ("Contacting Airglass," n.d.).

Table 2 TIM manufacturers

S.no	Manufacturer	Brand	TIM structure	Colour	Material
1	Wacotech	TIMax CA	Absorber-perpendicular - Honeycomb	Transparent	Cellulose triacetate
2	Wacotech	TIMax GL /S	Cavity structure	Translucent	glass fibres
3	Sto	StoSolar	Absorber-perpendicular – capillary system		
4	OKALUX	OKAPANE, KAPIPANE	Absorber-perpendicular, also available in	Transparent, White tinted	PMMA (acrylic)

S.no	Manufacturer	Brand	TIM structure	Colour	Material
		(honeycomb capillary system)	transitional geometry (intermediate between absorber-perpendicular and cavity structure)		
5	GAP solutions	Solar comb	Absorber-perpendicular - honeycomb	Black to light grey	Cardboard
6	COVESTRO	Makrolon® Multiwall	Cavity structure – Multichannel sheet	Clear, white, opal white	Polycarbonate
7	Advanced Glazing’s Ltd	Transparent InsolCore®	Absorber-perpendicular - honeycomb	Transparent	Polypropylene plastic film
8	CPI Daylighting	Pentaglas® - Nano-Cell® Technology	Cavity structure – Multichannel sheet with honeycomb cell structures	Range of colours – clear, white etc.	Polycarbonate
9	Kingspan Limited	Kingspan Architectural	Cavity structure	Translucent - range of colour	Polycarbonate
10	Pilkington	Pilkington Profilit™	Absorber-parallel	Translucent- range of colour	Profiled glass
11	SABIC	LEXAN™ Thermoclear™	Cavity structure - Multiwall sheet	Clear, opal white, IR green	Polycarbonate
12	CABOT corporation	Lumira® aerogel	Quasi-homogeneous – granular particles	Translucent	silica aerogel
13	Nano High-Tech Co. Ltd	Nanuo – Daylighting panel (TP)	Quasi-homogeneous - particles, films and plate materials	Translucent	Silica aerogel
14	Airglass AB	Airglass	Quasi-homogeneous - Monolithic	Translucent/ transparent	silica aerogels
15	Green Earth Aerogels Technologies	GEAT SILICA AEROGEL AAA	Quasi-homogeneous– Aerogel pellets	Translucent	Silica aerogel- from rice husk and residues
16	ENERSENS	Kwark® white	Quasi-homogeneous – granular particle	Translucent	Silica aerogel
17	JIOS Aerogel Corporation	JIOS AeroVa® Aerogel powder	Quasi-homogeneous - powder	White-translucent	Silica aerogel
18	Aerogel technologies. LLC	Classic Silica™ aerogels	Quasi-homogeneous - Monolithic	Translucent	Silica aerogel
19	Guangdong Alison Hi-Tech Co.,Ltd.	Alison Aerogel	Quasi-homogeneous - particles	Translucent	Silica aerogel

5.2 TI system manufacturers

TIM manufacturers listed in previous sections fabricate TI systems and distribute TIM to other fabricators to produce TI systems. A list of existing TI system manufacturers, their products, fundamental properties such as g-value and U-value with thickness and possible applications of these TI-systems are summarised in appendices 1 and 2. In addition to properties, the structural arrangement of TI system is also presented, for example, glass + honeycomb (TIM) + glass. Appendix 1 presents TI systems without aerogel and appendix 2 presents TI systems with aerogel. With this data from Appendices 1 and 2, two graphs are plotted as shown in Figure 7 and Figure 9 for comparison of existing products available by their thickness to U-value.

5.2.1 TI system without aerogel

Figure 7 shows the relationship between U-values and TIM thicknesses for a range of TI systems without aerogel using data from appendix 1. For comparison, TI systems with lowest U-values shown in appendix 1 have been considered in this graph. TI-systems with lower U-values are available, depending on customer's requirements, but these are customised systems and can be more expensive.

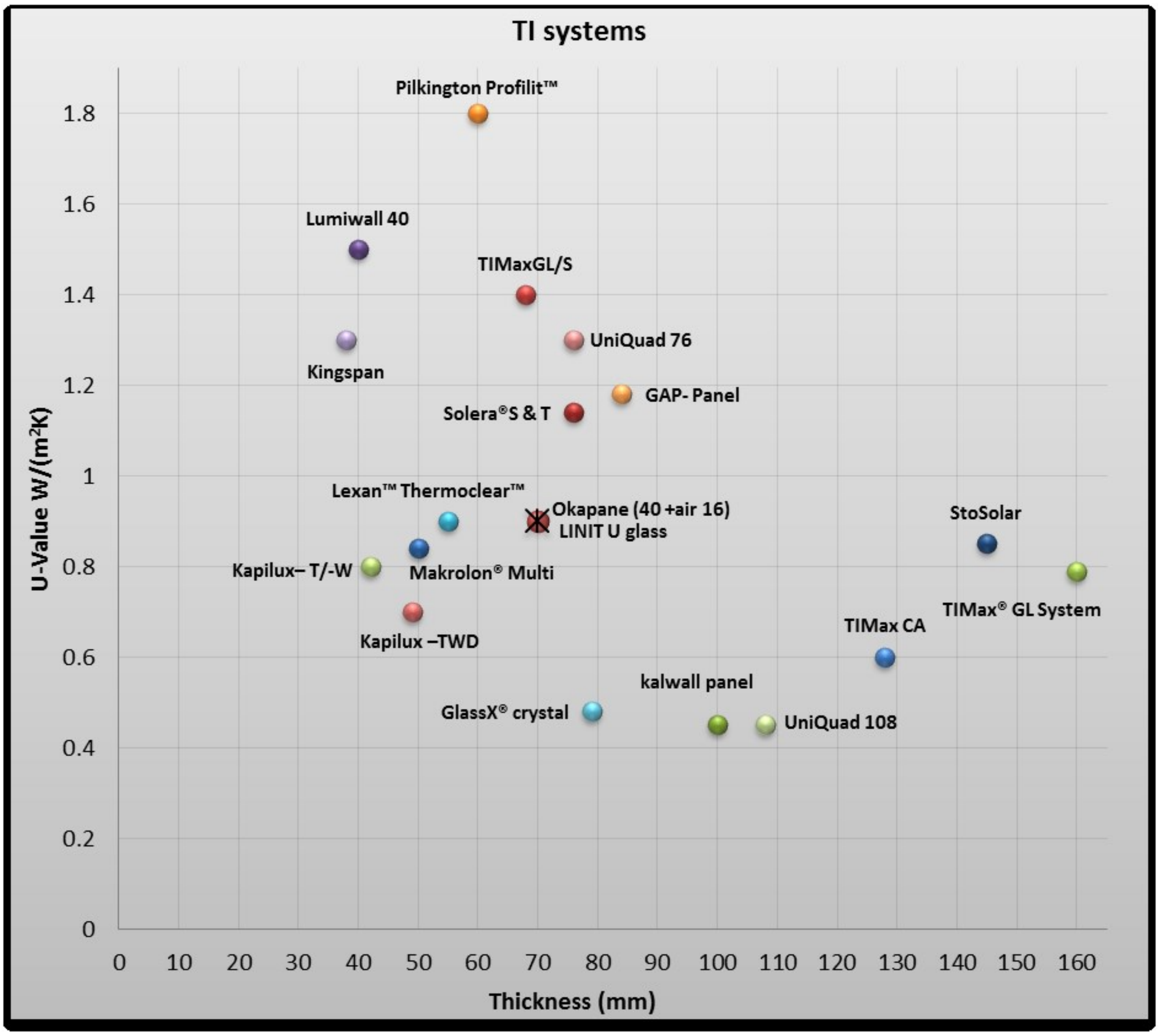

Figure 7 TI systems in the market without aerogel (Appendix 1)

Figure 7 shows that Kalwall panel Uniquad108 systems have the lowest U-value of 0.45 W/(m^{2}K). Along with lower U-value, the reduced thickness of the system is also very important for considerable weight reduction. Kalwall panel has a lower thickness than Uniquad, and both of these systems have low g-values of less than 10%. On the other hand, the Glass X system with U-value of 0.48 W/(m^{2}K) at a thickness of 79mm has better fundamental properties than the Kalwall and Uniquad systems. Glass X is 21mm thinner than the Kalwall panel and 29mm thinner than the Uniquad system, and has a vertical direct g-value of 48%. The structure of GlassX TI system presented in the graph has four tempered safety glass arranged as shown in Figure 8:

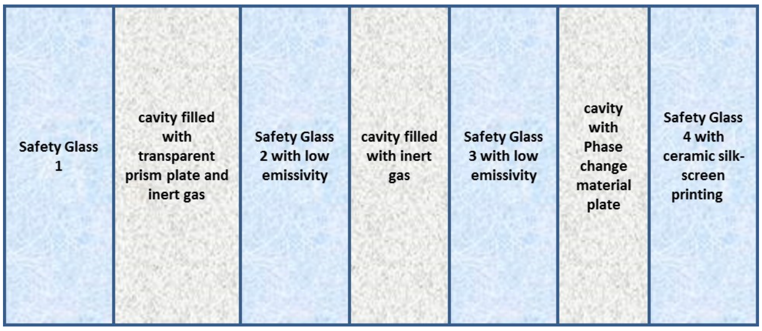

Figure 8 TI system - Glass X structural diagram("GLASSX AG - Products," n.d.)

The thickness, U-value and g-value of a TI-system affect the performance of the system. A TI-system with lower U-value, nominal thickness and average g-value is most suitable for different applications. The cost of the system also plays a significant role and it is essential to identify applications where expensive TI systems will be cost-efficient. Almost all TI systems listed in appendix 1 can be used for building insulation and daylighting, but there are also some systems which can be used for solar collectors, for example, Wacotech - TIMax CA.

Okalux TI system can be used for building façade, with a very low U-value of 0.7 W/ (m^2K), thickness of 49mm and g-value of 61%. It is possible to reduce a U-value in thinner systems by filling the TIM structure with inert gas between two glass panes. Polycarbonate systems by Makrolon and Lexan, have lower U-values and thicknesses because of multiwall polycarbonate structures with an air space in between. These multiwall polycarbonate structures can be further improved by filling with TIM for obtaining TI systems with lower U-values.

5.2.2 TI systems with aerogel

Appendix 2 shows TI systems with aerogel as TIM. Most of the TI system manufacturers use Lumira aerogel from Cabot Corporation for integration into their systems. Cabot has also formed a Lumira aerogel consortium in the USA to supply Lumira aerogel, and AmeriLux international is providing multiwall polycarbonate structures to fabricate with Lumira aerogel. Lumira aerogel consortium members are: - Cabot Corp -Lumira aerogel, Amerilux international - Multiwall Polycarbonate, Bristolite Daylighting Systems, Crystalit, Inc., Duo-Gard industries, Solar Innovations, Inc., Wasco skylight. This consortium is working on daylighting design challenges, thermal performance and design flexibility for sustainable designs. These consortium members are fabricating different TI systems using multiwall polycarbonate structures and Lumira aerogels. A list of consortium members and their products with lowest U-value are presented in appendix 2.

TI system manufacturers collaborating with Cabot Corp outside Lumira aerogel consortium to produce aerogel-filled TI systems are also listed in appendix 2. These manufacturers fabricate aerogel with their existing TIM structures to produce TI systems with low U-value. For example, Advanced Glazings Ltd fabricates TI systems by integrating Lumira aerogel in its patented honeycomb structure, a transparent InsolCore® made from polypropylene. Their aerogel-filled honeycomb TI system can achieve a U-value of 0.31 $W/(m^2K)$ with a thickness of 76.2 mm and g-value between 7 and 30%. Manufacturers such as ALCAUD SAS, ECODIS, ESSMANN GmBH, GUNISIGI, Roda, Skydome, Xtralite Rooflights, and Brett Martin Daylight Systems assemble Lumira aerogel in polycarbonate panels to produce TI systems. Gunisigi, a Turkish company, manufactures a 70mm aerogel-filled polycarbonate panel with a low U-value of 0.25 $W/(m^2K)$ and g-value of 19%. Some manufacturers, such as Technical Glass Products and Linit UK, fabricate aerogel-filled polycarbonate panels with double glazed 'U profile' glass to strengthen the structure for wall applications in buildings. Kalwall fabricates a TI panel with a U-value of 0.284 $W/(m^2K)$ and g-value of 25% by sandwiching Lumira aerogel in between fibre reinforced polymer sheets. One particular manufacturer is producing a translucent fabric with aerogels: Birdair, a USA based company, manufactures translucent and insulated tensile fabric roofing material, Tensotherm. Tensotherm is a composite material made of PTFE fibreglass fabric membrane and vapor barrier liner membrane with an aerogel-embedded translucent blanket in between. Tensotherm can achieve a U-value of 0.56 $W/(m^2K)$ with a thickness of 24 mm and g-value of 2.3%.

Figure 9 presents the comparison of different TI systems with aerogel of variable U-values and thicknesses currently available and shown in appendix 2. NanoLux, an aerogel-filled polycarbonate system has lowest U-value of 0.25 $W/(m^2K)$ with 70 mm thickness and g-value of 19%.

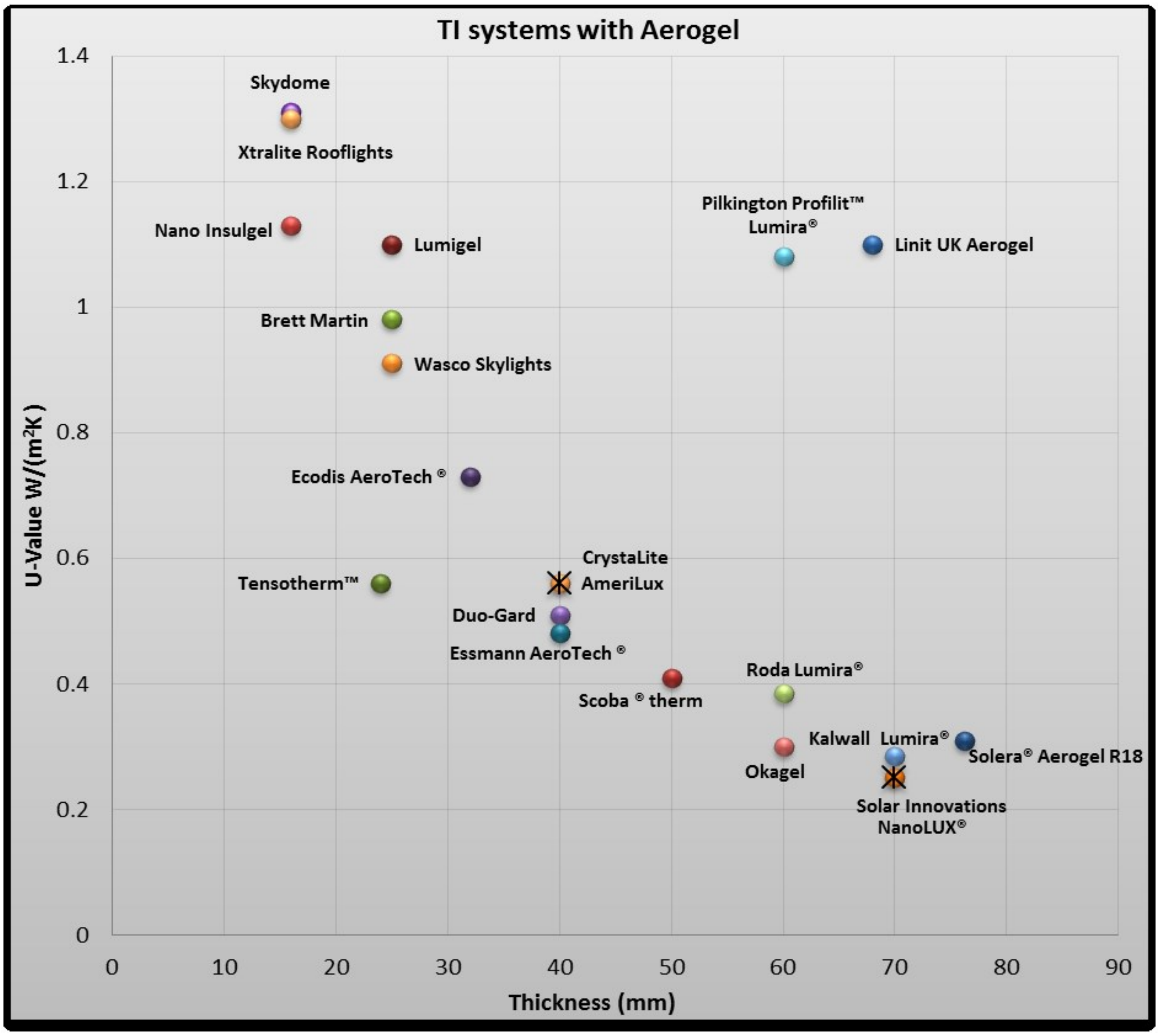

Figure 9 Available TI systems in the market with aerogel (Appendix 2)

5.2.3 Comparison of TI systems with and without aerogel

TIM can provide considerable weight and thickness reduction, which proves to be more resource-efficient for new buildings and in the old building retrofits compared with conventional glazings (Dowson, 2012).

Aerogel filled TI systems have further weight and thickness reduction with enhanced insulation properties compared with TI systems without aerogel. As shown in Figure 7 of TI systems without aerogel, Kalwall has the lowest U-value of 0.45 W/(m^{2}K) with 100mm thickness, whereas aerogel-filled TI systems (Figure 9) have lowest U-value of 0.25 W/(m^{2}K) with 70mm thickness and g-value of 19%. There are also aerogel-filled TI systems which can provide low U-value at a thickness of 16mm such as, Nanoinsugel (U-value of 1.13 W/(m^{2}K)) and Xtrarooflight (U-value of 1.3 W/(m^{2}K)). There is no availability of TI systems without aerogel currently with a thickness of 16mm and U-value lower than 1.5 W/(m^{2}K). Aerogel filled TI system of thickness 40mm with U-value lower than 0.6 W/(m^{2}K) are available in the market whereas TI systems without aerogel having U-value below 0.6 W/ (m^2K) are available from 79mm thickness systems. The comparison demonstrates that aerogel-filled TI systems can provide enhanced insulating properties at reduced weight and thickness with better g-values compared with other TI systems. Thus, aerogel-filled TI systems are a best fitted for retrofitting old buildings or in new buildings to conserve energy.

5.3 Drivers and barriers to the development of TI systems

5.3.1Drivers to development of TI systems

TIM is the state-of-the-art technology used in wide range of applications for thermal insulation and solar energy transmission. With the introduction of TIM in buildings to meet the zero-carbon building targets, research and development of TIM have gained momentum. In 1996, Platzer and Goetzberger estimated that over 85 buildings have 15000m^2 of TIM installed in Germany, Austria, and Switzerland for daylighting glazing in larger projects and solar wall application in smaller projects. They reported yearly installations of TIM for daylighting and solar wall applications, indicating market growth of TIM (Platzer and Goetzberger, 1996). In 1998 Platzer discussed the potential in building energy consumption reduction when TI systems were used for building retrofits. The heating energy consumption of the Paul Robeson School in Leipzig was reduced by 68.8% after a PMMA capillary-filled TI system was applied (Platzer, 1998). In 1999, Platzer and Wittwer reported more projects highlighting benefits of applying TI systems to buildings for reducing energy consumption (Wittwer and Platzer, 1999).

The International Energy Agency, under Solar Heating and Cooling (IEA-SHC) programme has been working on TIM development. Under this programme, the development of TIM has accelerated with increasing awareness on TIMs and their importance in building energy reduction. Energy simulation studies were carried out in IEA-SHC Task 18 on different advanced glazing materials to evaluate energy performance of these advance glazing systems in different countries. These studies show that using TIM as glazings in buildings have advantages over conventional glazings in reducing heat energy consumption. A simulation undertaken in Oslo and Tromso in Norway on different types of glazing showed lowest U-value of 0.7 W/(m^2K) and g-value of 0.64 could be achieved by aerogel-filled double glazing . Despite aerogel-filled double glazed windows achieving lowest heating demand, the cost-effectiveness of these windows could not be calculated as market prices were not available (Sullivan et al., 1995). Under IEA- SHC Task 20, TI systems were applied to building facades during building renovations in order to reduce energy demands for space heating and daylighting. Under Sub-task C of Task 20, designs have been developed for demonstration projects to renovate buildings with TI systems. Simulation results showed significant reduction in building energy consumption. As an example, the simulation results of renovation with TI facade on Valency building owned by Lausanne public utilities, Switzerland, exhibited a reduction in space heating net energy demand by 50%, whereas conventional renovation exhibited only 22% reduction. The study demonstrated that TI systems for renovation have large potential in saving heating energy. The results of these proposed demonstration projects were published in Sub-task E of task 20. New designs and concepts were developed and studied as cost reductions for TI systems for solar wall heating (Sub-Task F)(Arne Elmroth (S) et al., 1999, p. 20). In IEA SHC Task 37, silica aerogel was presented as a new technology in building envelopes best suited for facades, roof lights, and roofs of halls in buildings such as museums, sports facilities, administrative buildings and production halls. It was reported that aerogel-filled glazings are lighter than triple glazing, and are suitable for renovation projects due to structural requirement of having lighter components such as glazed roofs(Johann Reiss, 2011, p. 37). A solar collector system with an overheating prevention system developed by TIGI Limited was discussed in IEA-SHC Task 49 (Elimar Frank et al., 2015, p. 49). This collector used honeycomb TI system for reducing heat losses and achieved internal temperatures of over 250 $^{\circ}$C. To protect the system from overheating, a passive overheating prevention device (OPD) was introduced, which can retain high efficiency of collectors under normal working temperature and when pre-set temperature has reached 105 $^{\circ}$C it can quickly release thermal energy to atmosphere. Thus this OPD system can resolve the overheating problem in solar collectors while reducing the cost related to system-level overheating protection (Elimar Frank et al., 2015, p. 49). TIGI has planned and installed solar heating system at Golan Winery Limited in Katzrin, Israel/Syria. The solar heating system will provide a projected solar heat output of 247 MWh per year i.e. 70% of the yearly energy needed for heating the water(Bastian Schmitt and Stefan Hess, 2016, p. 49).

5.3.2 Barriers to development of TI systems

The key barriers to the development of TIM are manufacturing imperfections, low operating temperatures, overheating and high production cost (Wong et al., 2007). Platzer and Goetzberger (1996) claimed that TIM market penetration is slow due to high investment costs and no classification of TIM as a regular building product in European regulations (Platzer and Goetzberger, 1996). Platzer (1998) further identified lack in performance assessment of TIM while criticizing a small market for high costs (Platzer, 1998). Until 2000's TI systems were unknown among builders, suggesting the need for provision of widely available planning tools and information (Wittwer and Platzer, 1999).

TIM production has also not been straightforward. Platzer (1992) suggested that imperfections in the produced TIM honeycombs and capillaries can result in significant differences between measured and calculated values of solar transmission (Platzer, 1992b). Kaushika and Sumathy (2003) reported that fabrication of thick-walled TIM is simpler than thin-walled TIM because thin walled TIM can pose problems in glue dispensing. A new fabrication method (profile extrusion process) has been introduced to overcome this problem and to improve the quality of TIM. There has been significant progress in cost reduction of TIM with improved fabrication process (Kaushika and Sumathy, 2003).

Low working temperatures and overheating issues have been the constraints of TIM for applications at higher working temperatures. Wong et al. (2007) claimed that plastic TIMs have a low working temperature of approximately 80 $^{\circ}$C or lower. However, the working temperature of solar collectors can reach up to 250 $^{\circ}$C, which can cause overheating of TIM and consequently melting of TIM with system failure (Wong et al., 2007). In addition, Wong et al. (2007) state that overheating can be significant during summer months when TIM is applied over an extensive area of south-facing building facades. Thus expensive shading devices are required to prevent overheating, which would increase overall TI systems cost (Wong et al., 2007). Passive over-heating protection devices which can be applied to solar collectors shows progress on reducing overheating problem of TIM with cost-effective solutions (Elimar Frank et al., 2015, p. 49).

Silica aerogels which are a promising TIM with effective thermal insulation and high solar energy transmission, have been under rigorous research development (Berardi, 2015; Dowson, 2012; Duer and Svendsen, 1998; Reim et al., 2005, 2002; Schultz et al., 2005). Rubin and Lampert (1983) concluded that difficulties in production, long processing time, high fragility and tendency to adsorb water are key barriers in the development of silica aerogels (Rubin and Lampert, 1983). Pajonk (1998) reported an improvement in the synthesis of transparent aerogels with the introduction of supercritical drying liquid CO_2, which had reduced the time to obtain silica monolithic aerogels from 2-3 days to 8-10 hours depending on the thickness of the sample. With the reduction in processing time of aerogels, it is possible to make hydrophobic aerogels, which is significant progress in the development of silica aerogels (Pajonk, 1998). According to Schultz et al. (2005), optical transparency of monolithic silica aerogel is not as good as in a conventional glazing unit, and it requires further works to improve the clarity of monolithic silica aerogels to replace conventional glazings (Schultz et al., 2005). The fragile structure is one of the key issues which have prevented wider applications of silica aerogels. Berardi (2015) stated that it is not easy to produce large crack-free pieces of monolithic silica aerogels and the maximum size is currently 0.6 m x 0.6 m. Thus, monolithic silica aerogel panes have only been used in research, but granular aerogels are less fragile and easier to incorporate in different glazing systems (Berardi, 2015).

6. Recent Projects & Future development

This section details recent and future research programmes on the development of cost-efficient TI systems with better thermal and optical properties. Two completed research projects funded by European Commission (EC) and some ongoing research programmes funded by US Department of energy on TI systems are discussed.

6.1 CORDIS, European Commission (EC)

6.1.1 NANOINSULATE

Nanoinsulate is a project funded by EC-CORDIS to develop opaque and transparent vacuum insulation panels (VIP's) incorporating nanotechnology-based core materials for energy efficient buildings. These new systems have been developed by fabricating a VIP envelope over a nanotechnology-based core material such as nanofoams and aerogel composites. The core material for transparent VIP was developed by Airglass AB, Sweden, and KOC University, Turkey. A nano-monolithic composite of inorganic silica aerogels had been developed by incorporating a polymer in silica aerogel. A PDMS (OH)-silica aerogel composite was the most effective composite configuration found in the project. These composites have a lower transparency than aerogel, but the compressive strength is three times higher than aerogel. The aerogel composite core material is enclosed in a transparent novel VIP envelope developed by Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer IVV), Germany, and Hanita Coatings RCA Ltd., Israel. A transparent VIP panel was produced using VIP envelope and VIP core material, which has a thermal conductivity of 9 mW/(mK) and U-value of 0.45 W/(m^2K) at a thickness of 20mm (Kucukpinar et al., 2015). These VIP panels developed are up to 4 times more energy efficient than conventional insulation panels, which have extremely low thermal conductivity, superior mechanical properties and increased service life. The robust design of these panels provides a thinner and lightweight insulation solution suitable for new buildings as well as for building retrofits. This new transparent VIP panel will help in achieving zero-carbon building target by reducing heat losses and energy demand("European Commission : CORDIS : Projects & Results Service : Final Report Summary - NANOINSULATE (Development of Nanotechnology-based High-performance Opaque & Transparent Insulation Systems for Energy-efficient Buildings)," n.d.). It is concluded that it is possible to develop transparent gas-barrier envelope and aerogel composites for transparent VIP panel but to achieve cost-effectiveness and durability, these systems still require improvement (Kucukpinar et al., 2015).

6.1.2 BRIGHTWALL

BRIGHTWALL was an EC funded project, which had successfully developed a translucent insulated concrete panel prototype to replace traditional brick walls for building facades and load-bearing walls. This panel was developed by fabricating high-strength concrete over an insulating core material with optical fibre passing through them. The embedded optical fibre allows daylight to pass through the sandwich panel while insulating core provides thermal insulation. This concept of design can reduce thermal losses and energy demand. Brightwall panels with high structural strength can be used in new buildings or for building retrofits to meet architectural and aesthetic requirements. A fully functional prototype was installed in energy flex office at Danish Technological Institute ("European Commission : CORDIS : Projects & Results Service : Final Report Summary - BRIGHTWALL," 2016, "www.brightwallproject.eu," n.d.).

6.2 ARPA – E, US Department of energy

ARPA-E is a U.S Department of Energy organisation, which has announced many new projects on energy technologies. There are many new ongoing projects under SHIELD (Single-pane Highly Insulating Efficient Lucid Design) programme which involves the development of new coatings and windowpanes for energy efficiency. Some of the transparent and translucent insulation systems under development are described below:

6.2.1 AEROGEL INSULATED PANE

This project is carried out by Aspen Aerogels Inc. and partners to develop a cost-effective silica aerogel window to replace single pane windows in existing buildings. The proposed design is of a double glazed pane with aerogel sheet in between to provide high light transmittance, low haze and low thermal conductivity. This project will help to reduce building energy consumption by providing significant economic and environmental benefits ("ARPA-E | Aerogel Insulated Pane," 2016).

6.2.2 CROSSLINK AEROGELS

Undertaken by Virginia Commonwealth University and partners, the project aims to develop inexpensive and durable aerogel glass window panes for retrofitting single pane windows. Silica aerogels have superior insulating properties but are fragile and have high manufacturing costs. Newly developed cross-linked aerogels will be used for improved mechanical strength. An alternative drying method, freeze drying, is proposed in which production cost can be reduced by 40% compared to conventional supercritical drying. This proposed silica aerogel material is then sandwiched between the glass pane and polycarbonate films to provide an energy efficient window pane ("ARPA-E | Crosslink Aerogels," 2016).

6.2.3 WINDOW THERMAL BARRIER

Palo Alto Research Center (PARC) and partners are working on the development of a cost-effective, transparent thermal barrier using aerogel to improve insulation level of single pane windows. The proposed design consists of aerogel, glass and low emissivity coating. In this project the transparent polymer aerogel production process will be optimised, then aerogel will be integrated into a window pane, and finally, the performance of three-layered window pane will be evaluated. The final product will be an aerogel integrated window pane with a low manufacturing cost of USD 9 per square foot (USD 100 per square metre). This proposed thermal barrier window pane will have robust, lightweight design and low thermal conductivity ("ARPA-E | Window Thermal Barrier," 2016).

6.2.4 TRANSPARENT NANOFOAM POLYMER

Argonne National Laboratory and partners are seeking to develop a nanofoam polymer that can be embedded in a film or coating for single-pane windows to improve their thermal and sound insulation properties. For the proposed project hollow nano-particles with thin shells will be produced. These particles will be embedded uniformly in a polymer matrix. The nanofoams will be produced using low-cost manufacturing techniques while maintaining high transparency, enhanced thermal insulation and soundproofing. Polymer films and coatings produced from this project will be inexpensive and when applied on a single pane window will upgrade the windows performance to double glazed window at 25% of the cost of the double glazed window. This project provides a resourceful window film or coating design for effortless retrofitting of single pane windows with a reduction in building energy consumption ("ARPA-E | Transparent Nanofoam Polymer," 2016).

6.2.5 MULTIFUNCTIONAL GLAZING SYSTEM

Triton Systems, Inc. and partners are developing a high-efficiency window pane system. The proposed design integrates nanoparticle-polymer composite film with a porous material layer for better thermal insulation. This design will be an energy efficient direct glazing replacement for retrofitting single pane windows ("ARPA-E | Multifunctional Glazing System," 2016).

6.2.6 DYNAMIC IR WINDOW FILM

IR Dynamics and partners are working on a low-cost nanomaterial technology for better thermal insulation and solar heat gain in windows. The proposed design will incorporate cost efficient nanosheets for improving thermal insulation and nanomaterial for controlling solar heat gain depending on the outdoor weather. These materials will be used to create a window film for energy efficient retrofits on single pane windows ("ARPA-E | Dynamic IR Window Film," 2016).

The projects discussed above highlight the development of energy efficient TI systems for new buildings and for retrofitting existing building to achieve EU and US zero carbon building targets. TI systems used to provide daylight can reduce electricity required for lighting. According to Brightwall marketing project report (2015), lighting accounts for 15% of electricity consumption in EU. Ninety percent of the indoor working environment in the EU still relies on artificial lighting during daytime [138], and the EU has set a goal to reduce electricity consumption by 9% by the end of 2017. With the help of cost and energy efficient daylighting systems such as TI facades, these energy consumptions can be reduced by providing light gain and reducing thermal losses.

The market growth of TI systems has brought down the capital cost, but there is still a need for considerable improvement to develop new TI-systems with robust design and at lower cost, which can have better thermal insulation and daylighting performance compared with existing systems. The support provided by governments for the development of TI systems has led to the advancement of these technologies and low-cost solutions for different applications. These technologies can help to reduce energy consumption and achieve cost saving for positive environmental and economic effects.

7. Conclusion

This paper provides an overview of transparent insulation materials with detailed analysis and comparison of their geometrical classification, materials, and heat losses. Technological advances and the availability of new materials have led to the development of new TI-systems for various applications. A study of TI systems available to date shows absorber-perpendicular and quasi-homogeneous as the preferred geometrical structures for TIMs. The application of TI-systems in buildings is one of the most effective ways of TI-applications. Finally, a summary of existing TIM and TI-system manufacturers available in the market has been presented with thermal transmittance and solar energy transmittance. This characterisation shows design and development of the existing TIM geometries and their applications. The discussion on the recent and future projects shows continuous efforts in TIM development, which demonstrates that TI systems are promising technologies for insulation and daylighting. Quasi-homogeneous geometrical structures, in particular, aerogel, have emerged as one of the most effective TIMs, which can achieve U-value as low as 0.25 W/(m^2K) with a thickness of 70mm. According to the existing research, it is evident that incorporating aerogels in glazings at structural level provides better insulation. This review is suitable as the elemental reference for researchers, designers and developers to identify and select potential TIM for future development. It also provides a list of TI systems with the detailed thermal and solar transmittance, which are available to improve insulation level and daylighting performance in buildings.

Acknowledgements

The authors would like to take an opportunity to thank the School of Engineering and Built Environment at Glasgow Caledonian University for providing their support by funding the research work.

References

Abdul Mujeebu, M., Ashraf, N., Alsuwayigh, A.H., 2016. Effect of nano vacuum insulation panel and nanogel glazing on the energy performance of office building. Applied Energy 173, 141–151. https://doi.org/10.1016/j.apenergy.2016.04.014

Abdullah, A.H., Abou-Ziyan, H.Z., Ghoneim, A.A., 2003. Thermal performance of flat plate solar collector using various arrangements of compound honeycomb. Energy Conversion and Management 44, 3093–3112. https://doi.org/10.1016/S0196-8904(03)00013-X

Adriaansen, F., Thiagarajan, C., Suryawanshi, J.B., Aniruddha, M., 2005. Extruded transparent/translucent sheet for roof structures. US6931796 B2.

Aérogel Lumira - Skydôme provides natural lighting, ventilation and natural smoke evacuation systems [WWW Document], n.d. URL http://www.skydome.eu/en/profesional-product.php?id=39 (accessed 3.10.17).

Alcaud - sécurité incendie par le désenfumage naturel, de ventilation confort, de protection solaire et d'éclairage naturel [WWW Document], n.d. URL http://www.alcaud.fr/ (accessed 3.10.17).

Alison Aerogel -- Guangdong Alison Hi-Tech Co.,Ltd. [WWW Document], n.d. URL http://www.ydalison.com/en/product/ (accessed 3.9.17).

Alonso, L., Bedoya, C., Lauret, B., Alonso, F., 2012. High Energy Performance with Transparent (Translucent) Envelopes. https://doi.org/10.5772/37800

Alonso, L., Lauret, B., Alonso, F., 2011. Free-Form, High Energy Performance, Transparent Envelope. Advanced Materials Research 168–170, 1486–1490. https://doi.org/10.4028/www.scientific.net/AMR.168-170.1486

Arne Elmroth (S), Elisabeth Kjellsson (S), Hans-Jorg Althaus (CH), Chiel Boonstra (NL), Jan-Olof Dalenback (S), Geurt Donze (NL), Karel Fort (CH), Andreas Haller (CH, editor), Sheila Hayter (US), Olaf Bruun Jorgensen (DK), Micah Sherman (USA), Henrik Sorensen (DK), Karsten Voss (D), Tom Wood (USA), 1999. IEA Solar Heating and Cooling Programme Task 20 "Solar Energy in Building Renovation" Subtask F: "Improvement of Solar Renovation Concepts and Systems" (Technical Report No. Task 20 STF N12). International Energy Agency-Solar Heating and Cooling Task,20.

ARPA-E | Aerogel Insulated Pane [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/aerogel-insulated-pane (accessed 3.9.17).

ARPA-E | Crosslink Aerogels [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/crosslink-aerogels (accessed 3.9.17).

ARPA-E | Dynamic IR Window Film [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/dynamic-ir-window-film (accessed 3.9.17).

ARPA-E | Multifunctional Glazing System [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/multifunctional-glazing-system (accessed 3.9.17).

ARPA-E | Transparent Nanofoam Polymer [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/transparent-nanofoam-polymer (accessed 3.9.17).

ARPA-E | Window Thermal Barrier [WWW Document], 2016. URL https://arpa-e.energy.gov/?q=slick-sheet-project/window-thermal-barrier (accessed 3.9.17).

Avanti, P., Arulanantham, M., Kaushika, N.D., 1996. Solar thermal analysis of transparent-honeycomb-insulated ground collector-storage system. Applied Thermal Engineering 16, 863–874. https://doi.org/10.1016/1359-4311(96)00006-3

Baetens, R., Jelle, B.P., Gustavsen, A., 2011. Aerogel insulation for building applications: A state-of-the-art review. Energy and Buildings 43, 761–769. https://doi.org/10.1016/j.enbuild.2010.12.012

Bastian Schmitt, Stefan Hess, 2016. IEA SHC Task 49/IV - Deliverable C4 - Best practise series of case study reports from demonstration projects (SemiAnnual status report No. Devliverable C4). International Energy Agency-Solar Heating and Cooling Task, 49.

Berardi, U., 2015. The development of a monolithic aerogel glazed window for an energy retrofitting project. Applied Energy 154, 603–615. https://doi.org/10.1016/j.apenergy.2015.05.059

Bristolite Daylighting Systems [WWW Document], n.d. URL http://bristolite.com/interfaces/nano_insulgel.aspx (accessed 3.10.17).

Buratti, C., Moretti, E., 2012a. Experimental performance evaluation of aerogel glazing systems. Applied Energy, Energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy 97, 430–437. https://doi.org/10.1016/j.apenergy.2011.12.055

Buratti, C., Moretti, E., 2012b. Glazing systems with silica aerogel for energy savings in buildings. Applied Energy 98, 396–403. https://doi.org/10.1016/j.apenergy.2012.03.062

Buratti, C., Moretti, E., 2011. Lighting and Energetic Characteristics of Transparent Insulating Materials: Experimental Data and Calculation. Indoor and Built Environment 20, 400–411. https://doi.org/10.1177/1420326X11409470

Buratti, C., Moretti, E., Zinzi, M., 2017. High Energy-Efficient Windows with Silica Aerogel for Building Refurbishment: Experimental Characterization and Preliminary Simulations in Different Climate Conditions. Buildings 7, 8. https://doi.org/10.3390/buildings7010008

Buy Aerogel Materials Online | Aerogel Technologies, 2017. URL http://www.aerogeltechnologies.com/aerogel-materials (accessed 3.9.17).

Cai, Q., Ye, H., Lin, Q., 2016. Analysis of the optical and thermal properties of transparent insulating materials containing gas bubbles. Applied Thermal Engineering 100, 468–477. https://doi.org/10.1016/j.applthermaleng.2016.02.041

Chaurasia, P.B.L., Twidell, J., 2001. Collector cum storage solar water heaters with and without transparent insulation material. Solar Energy 70, 403–416. https://doi.org/10.1016/S0038-092X(00)00158-4

Communications, C.A., n.d. Covestro Sheets Europe - Makrolon® Multiwall Sheets [WWW Document]. URL http://www.sheets.covestro.com/en/Products/Europe/Makrolon-Multiwall-Sheets (accessed 3.9.17).

Contacting Airglass [WWW Document], n.d. URL http://www.airglass.se/contact.html (accessed 3.9.17).

Cotana, F., Pisello, A.L., Moretti, E., Buratti, C., 2014. Multipurpose characterization of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and acoustic performance. Building and Environment 81, 92–102. https://doi.org/10.1016/j.buildenv.2014.06.014

CPI daylighting [WWW Document], n.d. URL http://www.cpidaylighting.com/product.php?Single-Panel-Translucent-Wall-Cladding-77? (accessed 3.9.17).

Daylighting Systems with Lumira Aerogel - Lightweight Polycarbonate Panel Skylights [WWW Document], n.d. . Wasco Skylights. URL https://www.wascoskylights.com/product/lumira-aerogel/ (accessed 3.10.17).

Dowson, M., 2012. Novel retrofit technologies incorporating silica aerogel for lower energy buildings (Thesis). Brunel University School of Engineering and Design Theses.

Dowson, M., Harrison, D., Craig, S., Gill, Z., 2011. Improving the thermal performance of single-glazed windows using translucent granular aerogel. International Journal of Sustainable Engineering 4, 266–280. https://doi.org/10.1080/19397038.2011.558931

Dowson, M., Harrison, D., Dehouche, Z., 2014. Trombe walls with nanoporous aerogel insulation applied to UK housing refurbishments. International Journal of Smart and Nano Materials 5, 283–303. https://doi.org/10.1080/19475411.2014.999730

Dowson, M., Pegg, I., Harrison, D., Dehouche, Z., 2012. Predicted and in situ performance of a solar air collector incorporating a translucent granular aerogel cover. Energy and Buildings 49, 173–187. https://doi.org/10.1016/j.enbuild.2012.02.007

Duer, K., Svendsen, S., 1998. Monolithic silica aerogel in superinsulating glazings. Solar Energy 63, 259–267. https://doi.org/10.1016/S0038-092X(98)00063-2

ECODIS AEROTECH | Ecodis [WWW Document], n.d. URL http://www.ecodis.fr/en/product/ecodis-aerotech (accessed 3.10.17).

Elimar Frank, Franz Mauthner, Stephan Fischer, 2015. IEA SHC Task 49/IV - Deliverable A1.2 - Overheating prevention and stagnation handling in solar process heat applications (Technical Report No. A.1.2). International Energy Agency-Solar Heating and Cooling Task, 49.

Enersens Aerogels | High Performance Silica Aerogel, n.d. URL http://enersens.fr/en/home/ (accessed 3.9.17).

ESSMANN | ESSMANN AeroTech [WWW Document], n.d. URL http://www.essmann.co.uk/en/press/2010-archive/essmann-aerotech.html (accessed 3.10.17).

European Commission : CORDIS : Projects & Results Service : Final Report Summary - BRIGHTWALL [WWW Document], 2016. URL http://cordis.europa.eu/result/rcn/186857_en.html (accessed 3.9.17).

European Commission : CORDIS : Projects & Results Service : Final Report Summary - NANOINSULATE (Development of Nanotechnology-based High-performance Opaque & Transparent Insulation Systems for Energy-efficient Buildings) [WWW Document], n.d. URL http://cordis.europa.eu/result/rcn/172099_en.html (accessed 3.2.17).

Flynn, G., Carolan, J., 2012. Translucent panel. US8316598 B2.

Francia, G., 1963. A new collector of solar radiant energy—Theory and experimental verification. Solar Energy 7, 145–146. https://doi.org/10.1016/0038-092X(63)90053-7

Fuji, M., Takai, C., Watanabe, H., Fujimoto, K., 2015. Improved transparent thermal insulation using nano-spaces. Advanced Powder Technology, Special issue of the 7th World Congress on Particle Technology 26, 857–860. https://doi.org/10.1016/j.apt.2015.02.012

Gao, T., Jelle, B.P., Ihara, T., Gustavsen, A., 2014. Insulating glazing units with silica aerogel granules: The impact of particle size. Applied Energy 128, 27–34. https://doi.org/10.1016/j.apenergy.2014.04.037

GAP: GAP Solutions GmbH [WWW Document], n.d. URL http://www.gap-solutions.at/en/ (accessed 3.9.17).

Garnier, C., Muneer, T., McCauley, L., 2015. Super insulated aerogel windows: Impact on daylighting and thermal performance. Building and Environment 94, Part 1, 231–238. https://doi.org/10.1016/j.buildenv.2015.08.009

Ghoneim, A.A., 2005. Performance optimization of solar collector equipped with different arrangements of square-celled honeycomb. International Journal of Thermal Sciences 44, 95–105.

Giovanetti, F., Kirchner, M., Rockendorf, G., Kehl, O., 2011. Cellulose triacetate honeycombs compounds for improved flat plate collectors: performance and reliability, in: Proceeding of ISES Solar World Congress, Kassel, Germany.

Glasfabrik Lamberts GmbH & Co. KG: Lamberts Linit [WWW Document], n.d. URL http://www.lamberts.info/en/lamberts-linit/ (accessed 3.9.17).

GLASSX AG - Products [WWW Document], n.d. URL http://glassx.ch/index.php?id=331 (accessed 3.9.17).

Goetzberger, A., 1987. Potential uses of transparent insulation materials for thermal collectors and in buildings. Solar & Wind Technology 4, 389–393. https://doi.org/10.1016/0741-983X(87)90069-5

Goetzberger, A., Schmid, J., Wittwer, V., 1984. Transparent Insulation System for Passive Solar Energy Utilization in Buildings, in: Ouden, C.D. (Ed.), First E.C. Conference on Solar Heating. Springer Netherlands, pp. 314–318. https://doi.org/10.1007/978-94-009-6508-9_55

Grilikhes, V.A., 2007. On the 100th anniversary of the birth of Vsevolod Borisovich Veinberg. Appl. Sol. Energy 43, 61–64. https://doi.org/10.3103/S0003701X07010215

Groothues, H., Mende, V., Lorenz, H., Scharnke, W., Ittmann, G., Hasskerl, T., Brand, N., Schaefer, B., 2004. Plastic body having low thermal conductivity, high light transmission and a capacity for absorption in the near-infrared region. US20040191485 A1.

Günışığı Aydınlatma [WWW Document], n.d. URL http://www.gunisigiaydinlatma.com/Product/Nanoluxs (accessed 3.10.17).

High Performance Energy Management and Savings with Lumira® aerogel, n.d. . Duo-Gard. URL http://www.duo-gard.com/sustainabilities-technologies/lumira-aerogel/ (accessed 3.10.17).

Hollands, K.G.T., 1965. Honeycomb devices in flat-plate solar collectors. Solar Energy 9, 159–164. https://doi.org/10.1016/0038-092X(65)90089-7

Hollands, K.G.T., Marshall, K.N., Wedel, R.K., 1978. An approximate equation for predicting the solar transmittance of transparent honeycombs. Solar Energy 21, 231–236. https://doi.org/10.1016/0038-092X(78)90026-9

Home, 2015. . Kalwall. URL https://www.kalwall.com/ (accessed 3.9.17).

Home - KIP Division - Kingspan Insulated Panels UK & Ire [WWW Document], n.d. URL http://www.kingspanpanels.co.uk/ (accessed 3.9.17).

Home [WWW Document], n.d. . Cabot Corporation. URL http://www.cabotcorp.com/ (accessed 3.9.17).

Huang, L., 2012. Feasibility study of using silica aerogel as insulation for buildings. Master of Science thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden.

Huang, Y., Niu, J., 2015. Application of super-insulating translucent silica aerogel glazing system on commercial building envelope of humid subtropical climates – Impact on space cooling load. Energy 83, 316–325. https://doi.org/10.1016/j.energy.2015.02.027

Hum, J.E.Y., Hollands, K.G.T., Wright, J.L., 2004. Analytical model for the thermal conductance of double-compound honeycomb transparent insulation, with validation. Solar Energy, Solar World Congress 2001 76, 85–91. https://doi.org/10.1016/j.solener.2003.07.034

Ihara, T., Grynning, S., Gao, T., Gustavsen, A., Jelle, B.P., 2015. Impact of convection on thermal performance of aerogel granulate glazing systems. Energy and Buildings 88, 165–173. https://doi.org/10.1016/j.enbuild.2014.12.001

info Lumira [WWW Document], n.d. URL https://www.roda.de/products/daylight-technology/lumira-aerogel/info/ (accessed 3.10.17).

Insulated Tensioned Membrane - Fabric Membranes | Birdair, Inc. [WWW Document], n.d. URL http://www.birdair.com/tensile-architecture/membrane/insulated-tensioned-membrane (accessed 3.10.17).

Jensen, K.I., Schultz, J.M., Kristiansen, F.H., 2004. Development of windows based on highly insulating aerogel glazings. Journal of Non-Crystalline Solids, Aerogels 7. Proceedings of the 7th International Symposium on Aerogels7th International Symposium on Aerogels 350, 351–357. https://doi.org/10.1016/j.jnoncrysol.2004.06.047

JIOS Aerogel » JIOS AeroVa® Aerogel Powder, n.d. URL http://www.jiosaerogel.com/aerova-aerogel-powder/ (accessed 3.9.17).

Johann Reiss, 2011. IEA SHC Task 37, Advances in Housing Renovation- Processes, Concepts and Technologies - Silica Aerogel Granulate. Fraunhofer-Institute for Solar Energy Systems ISE, International Energy Agency - Solar Heating and cooling Programme task 37.

Kaushika, N.D., Banerjee, M.B., 1985. Thermal analysis of honeycomb solar pond. Energy Conversion and Management 25, 3–7. https://doi.org/10.1016/0196-8904(85)90062-7

Kaushika, N.D., Priya, R.P., 1991. Solar transmittance of honeycomb and parallel slat arrays. Energy Conversion and Management 32, 345–351. https://doi.org/10.1016/0196-8904(91)90052-K

Kaushika, N.D., Reddy, K.S., 1999. Thermal design and field experiment of transparent honeycomb insulated integrated-collector-storage solar water heater. Applied Thermal Engineering 19, 145–161. https://doi.org/10.1016/S1359-4311(98)00033-7

Kaushika, N.D., Sharma, P.P., 1994. Transparent honeycomb insulated solar thermal systems for energy conservation. Heat Recovery Systems and CHP 14, 37–44. https://doi.org/10.1016/0890-4332(94)90069-8

Kaushika, N.D., Sumathy, K., 2003. Solar transparent insulation materials: a review. Renewable and Sustainable Energy Reviews 7, 317–351. https://doi.org/10.1016/S1364-0321(03)00067-4

Kessentini, H., Capdevila Paramio, R., Castro González, J., Oliva Llena, A., 2011. Numerical and experimental study of a flat plate solar collector with transparent insulation and overheating protection system. Presented at the Proceedings of ISES Solar World Congress 2011, pp. 2946–2957.

Kessentini, H., Castro, J., Capdevila, R., Oliva, A., 2014. Development of flat plate collector with plastic transparent insulation and low-cost overheating protection system. Applied Energy 133, 206–223. https://doi.org/10.1016/j.apenergy.2014.07.093

Kucukpinar, E., Miesbauer, O., Carmi, Y., Fricke, M., Gullberg, L., Erkey, C., Caps, R., Rochefort, M., Moreno, A.G., Delgado, C., Koehl, M., Holdsworth, P., Noller, K., 2015. Development of Transparent and Opaque Vacuum Insulation Panels for Energy Efficient Buildings. Energy Procedia, 6th

International Building Physics Conference, IBPC 2015 78, 412–417. https://doi.org/10.1016/j.egypro.2015.11.685

LEXAN™ THERMOCLEAR™ Sheet [WWW Document], n.d. . SABIC Innovative Plastics. URL https://sfs.sabic.eu/product/lexan-thermoclear-sheet/ (accessed 3.9.17).

Lien, A.G., Hestnes, A.G., Aschehoug, Ø., 1997. The use of transparent insulation in low energy dwellings in cold climates. Solar Energy, Selected Proceedings of ISES 1995: Solar World Congress. Part III 59, 27–35. https://doi.org/10.1016/S0038-092X(96)00120-X

Linit Insulation - Linit UK [WWW Document], n.d. URL http://www.linituk.com/linit-insulation.html (accessed 3.9.17).

Lumira® aerogel enhances mutiwall polycarbonate systems insulation. [WWW Document], n.d. URL http://www.ameriluxinternational.com/lumira.php (accessed 3.10.17).

Lumira ® Aerogel, n.d. . Solar Innovations. URL http://solarinnovations.com/parts/lumira/ (accessed 3.10.17).

Lumira Aerogel | CrystaLite, Inc. [WWW Document], n.d. URL http://www.crystaliteinc.com/pages/products/lumira/ (accessed 3.10.17).

Marshall, K.N., Wedel, R.K., Dammann, R.E., 1976. Development of Plastic Honeycomb Flat-Plate Solar Collectors (No. SAN-1081-76/1; LMSC/D-462879). Lockheed Missiles and Space Co., Palo Alto, CA (USA).

Milburn, D.I., 2004. Honeycomb transparent insulation with improved insulating ability. US6699559 B1.

Milburn, D.I., 2003. Insulated greenhouse. US6594957 B1.

Moretti, E., Zinzi, M., Belloni, E., 2014. Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance. Energy and Buildings 70, 23–35. https://doi.org/10.1016/j.enbuild.2013.11.045

Nahar, N.M., 2001. Design, development and testing of a double reflector hot box solar cooker with a transparent insulation material. Renewable Energy 23, 167–179. https://doi.org/10.1016/S0960-1481(00)00178-6

Nano Tech Co., Ltd. - aerogel, aerogel blanket, insulation Panel, aerogel felt, thermal insulation [WWW Document], n.d. URL http://nanuoaerogel.en.ec21.com/ (accessed 3.9.17).

News & Events | Lumira Aerogel | Brett Martin [WWW Document], n.d. URL http://www.brettmartin.com/en-gb/daylight-systems/news-events/lumira-aerogel.aspx (accessed 3.10.17).

Nordgaard, A., Beckman, W.A., 1992. Transparent insulationModelling of flat-plate collectors based on monolithic silica aerogel. Solar Energy 49, 387–402. https://doi.org/10.1016/0038-092X(92)90111-M

OKAGEL [WWW Document], n.d. URL http://www.okalux.com/solutions/brands/okagel/ (accessed 3.10.17).

OKALUX GmbH [WWW Document], n.d. URL http://www.okalux.de/ (accessed 3.9.17).

Pajonk, G.M., 1998. Transparent silica aerogels. Journal of Non-Crystalline Solids 225, 307–314. https://doi.org/10.1016/S0022-3093(98)00131-8

Pellette, P., Cobble, M., Smith, P., 1968. Honeycomb thermal trap. Solar Energy 12, 263–265. https://doi.org/10.1016/0038-092X(68)90012-1

Pflüger, A., 1987. Minimum thermal conductivity of transparent insulation materials. Solar Energy Materials 16, 255–265. https://doi.org/10.1016/0165-1633(87)90025-6

Pilkington Profilit with Lumira Aerogel | Insulated Channel Glass [WWW Document], n.d. URL http://www.tgpamerica.com/structural-glass/pilkington-profilit-insulation/ (accessed 3.10.17).

Pilkington Profilit^{TM} [WWW Document], n.d. URL http://www.pilkington.com/en-gb/uk/products/product-categories/glass-systems/pilkington-profilit (accessed 3.9.17).

Platzer, W.J., 1998. ADVANCES AND PROBLEMS OF TRANSPARENT INSULATION IN THE MARKET Professionalization and Diversification, in: EuroSun 98 : The Second ISES Europe Solar Congress : Book of Proceedings. Birmingham : Franklin Company Consultants, 1999., Portorož, Slovenia, p. VI.4-1.

Platzer, W.J., 1992a. Calculation procedure for collectors with a honeycomb cover of rectangular cross section. Solar Energy 48, 381–393. https://doi.org/10.1016/0038-092X(92)90047-E

Platzer, W.J., 1992b. Directional-hemispherical solar transmittance data for plastic honeycomb-type structures. Solar Energy 49, 359–369. https://doi.org/10.1016/0038-092X(92)90108-M

Platzer, W.J., 1992c. Total heat transport data for plastic honeycomb-type structures. Solar Energy 49, 351–358. https://doi.org/10.1016/0038-092X(92)90107-L

Platzer, W.J., 1987. Solar transmission of transparent insulation material. Solar Energy Materials 16, 275–287. https://doi.org/10.1016/0165-1633(87)90027-X

Platzer, W.J., Goetzberger, A., 1996. Recent advances in transparent insulation technology, in: Proceedings of Eighth Workshop on Transparent Insulation (TI8).

Products of GEAT [WWW Document], n.d. URL http://www.green-earth-aerogel.com/geat/products.htm (accessed 3.9.17).

Qu, J., Song, J., Qin, J., Song, Z., Zhang, W., Shi, Y., Zhang, T., Zhang, H., Zhang, R., He, Z., Xue, X., 2014. Transparent thermal insulation coatings for energy efficient glass windows and curtain walls. Energy and Buildings 77, 1–10. https://doi.org/10.1016/j.enbuild.2014.03.032

Reddy, K.S., 2007. Thermal Modeling of PCM-Based Solar Integrated Collector Storage Water Heating System. J. Sol. Energy Eng 129, 458–464. https://doi.org/10.1115/1.2770753

Reglit Glass Architecture / Pilkington Profilit U-Profiled Glass [WWW Document], n.d. . Reglit Glass Architecture / Pilkington Profilit U-Profiled Glass. URL http://www.reglit.com (accessed 3.9.17).

Reim, M., Beck, A., Körner, W., Petricevic, R., Glora, M., Weth, M., Schliermann, T., Fricke, J., Schmidt, C., Pötter, F.J., 2002. Highly insulating aerogel glazing for solar energy usage. Solar Energy 72, 21–29. https://doi.org/10.1016/S0038-092X(01)00086-X

Reim, M., Körner, W., Manara, J., Korder, S., Arduini-Schuster, M., Ebert, H.-P., Fricke, J., 2005. Silica aerogel granulate material for thermal insulation and daylighting. Solar Energy, CISBAT '03: Innovation in Building Envelopes and Environmental Systems 79, 131–139. https://doi.org/10.1016/j.solener.2004.08.032

Rubin, M., Lampert, C.M., 1983. Transparent silica aerogels for window insulation. Solar Energy Materials 7, 393–400. https://doi.org/10.1016/0165-1633(83)90012-6

Schultz, J.M., Jensen, K.I., 2008. Evacuated aerogel glazings. Vacuum, The World Energy Crisis Part 2: Some More Vacuum-based Solutions 82, 723–729. https://doi.org/10.1016/j.vacuum.2007.10.019

Schultz, J.M., Jensen, K.I., Kristiansen, F.H., 2005. Super insulating aerogel glazing. Solar Energy Materials and Solar Cells, EuroSun2004EuroSun2004 89, 275–285. https://doi.org/10.1016/j.solmat.2005.01.016

Sharma, M.S., Kaushika, N.D., 1987. Design and performance characteristics of honeycomb solar pond. Energy Conversion and Management 27, 111–116. https://doi.org/10.1016/0196-8904(87)90061-6

Solera® + Aerogel R18 | Advanced Glazings, n.d. URL http://www.advancedglazings.com/product-overview/solera-aerogel-r18/ (accessed 3.10.17).

Solera | Architectural Daylighting - AdvancedGlazings.com, n.d. URL http://www.advancedglazings.com/ (accessed 3.9.17).

Sridhar, A., Reddy, K.S., 2007. Transient analysis of modified cuboid solar integrated-collector-storage system. Applied Thermal Engineering 27, 330–346. https://doi.org/10.1016/j.applthermaleng.2006.07.040

Stahl, W., Wittwer, V., Pflüger, A., 1984. Transparent insulation. Solar Energy Materials 11, 199–208. https://doi.org/10.1016/0165-1633(84)90071-6

StoSolar: tot 95% rendement uit zonne-energie | Sto [WWW Document], n.d. URL http://www.sto.nl/nl/over-ons/innovaties/stosolar/stosolar_rendement_zonne_energie.html (accessed 3.9.17).

Structural Glazing Lumira [WWW Document], n.d. URL http://www.xtralite.co.uk/products/category/structural-glazing-glass/46/ (accessed 3.10.17).

Suehrcke, H., Däldehög, D., Harris, J.A., Lowe, R.W., 2004. Heat transfer across corrugated sheets and honeycomb transparent insulation. Solar Energy, Solar World Congress 2001 76, 351–358. https://doi.org/10.1016/j.solener.2003.08.023

Sullivan, R., Selkowitz, S., Lyons, P., 1995. Energy Simulation Studies in Iea/Shc Task 18 Advanced Glazing and Associated Materials for Solar and Building Applications (No. LBL--37024; CONF-9506177--2). Lawrence Berkeley Lab., CA (United States).

Sun, Y., Wu, Y., Wilson, R., 2017. Analysis of the daylight performance of a glazing system with Parallel Slat Transparent Insulation Material (PS-TIM). Energy and Buildings 139, 616–633. https://doi.org/10.1016/j.enbuild.2017.01.001

Sun, Y., Wu, Y., Wilson, R., Lu, S., 2016a. Experimental measurement and numerical simulation of the thermal performance of a double glazing system with an interstitial Venetian blind. Building and Environment 103, 111–122. https://doi.org/10.1016/j.buildenv.2016.03.028

Sun, Y., Wu, Y., Wilson, R., Sun, S., 2016b. Thermal evaluation of a double glazing façade system with integrated Parallel Slat Transparent Insulation Material (PS-TIM). Building and Environment 105, 69–81. https://doi.org/10.1016/j.buildenv.2016.05.004

Supramat Swiss - scoba®element / therm [WWW Document], n.d. URL http://www.supramat-swiss.ch/produkte/scobarelementtherm.html (accessed 3.10.17).

Swinkels, G., Sonneveld, P.J., Bot, G.P.A., 2001. SE—Structures and Environment: Improvement of Greenhouse Insulation with Restricted Transmission Loss through Zigzag Covering Material. Journal of Agricultural Engineering Research 79, 91–97.

Symons, J.G., 1982. The Solar Transmittance of Some Convection Suppression Devices for Solar Energy Applications: An Experimental Study. J. Sol. Energy Eng 104, 251–256. https://doi.org/10.1115/1.3266309

Tabor, H., 1969. Cellular insulation (honeycombs). Solar Energy 12, 549–552. https://doi.org/10.1016/0038-092X(69)90079-6

Thermal Performance, 2015. . Kalwall. URL https://www.kalwall.com/technology/performance/thermal-performance/ (accessed 3.10.17).

wacotech [WWW Document], n.d. URL https://www.wacotech.de/wacotech_en/ (accessed 2.26.17).

Wallner, G.M., Hausner, R., Hegedys, H., Schobermayr, H., Lang, R.W., 2006. Application demonstration and performance of a cellulose triacetate polymer film based transparent insulation wall heating system.

Solar Energy, European Solar Conference (EuroSun 2004)EuroSun Conference 2004 80, 1410–1416. https://doi.org/10.1016/j.solener.2006.05.007

Wallner, G.M., Lang, R.W., 2005. Aging of polymeric films for transparent insulation wall applications. Solar Energy, Polymeric Materials for Solar Energy Applications 79, 603–611. https://doi.org/10.1016/j.solener.2005.05.001

Wallner, G.M., Lang, R.W., Schobermayr, H., Hegedys, H., Hausner, R., 2004. Development and application demonstration of a novel polymer film based transparent insulation wall heating system. Solar Energy Materials and Solar Cells, International Solar Energy Society World Congress 2003 84, 441–457. https://doi.org/10.1016/j.solmat.2004.01.047

Wallner, G.M., Platzer, W., Lang, R.W., 2005a. Structure–property correlations of polymeric films for transparent insulation wall applications. Part 2: Infrared optical properties. Solar Energy, Polymeric Materials for Solar Energy Applications 79, 593–602. https://doi.org/10.1016/j.solener.2005.05.007

Wallner, G.M., Platzer, W., Lang, R.W., 2005b. Structure–property correlations of polymeric films for transparent insulation wall applications. Part 1: Solar optical properties. Solar Energy, Polymeric Materials for Solar Energy Applications 79, 583–592. https://doi.org/10.1016/j.solener.2005.05.006

Wasco Skylights for Commercial and Residential Daylighting [WWW Document], n.d. . Wasco Skylights. URL https://www.wascoskylights.com/ (accessed 3.9.17).

Wittwer, V., 1994. The use of transparent insulation materials and optical switching layers in window systems. Renewable Energy 5, 318–323. https://doi.org/10.1016/0960-1481(94)90389-1

Wittwer, V., Platzer, W., 1999. Transparent thermal insulation materials and systems: state of the art and potential for the future.

Wong, I.L., Eames, P., 2015. A method for calculating the solar transmittance, absorptance and reflectance of a transparent insulation system. Solar Energy 111, 418–425. https://doi.org/10.1016/j.solener.2014.09.028

Wong, I.L., Eames, P.C., Perera, R.S., 2007. A review of transparent insulation systems and the evaluation of payback period for building applications. Solar Energy, CISBAT 2005 81, 1058–1071. https://doi.org/10.1016/j.solener.2007.04.004

www.brightwallproject.eu [WWW Document], n.d. URL http://www.brightwallproject.eu/progress.aspx (accessed 3.9.17).

Yang, H., Zhu, Z., Burnett, J., 2000. Simulation of the behaviour of transparent insulation materials in buildings in northern China. Applied Energy 67, 293–306. https://doi.org/10.1016/S0306-2619(00)00022-2

Appendix 1 – TI System manufacturers without aerogel

Table A. 1

S.No	Manufacturer	Product name	Material type/make-up	Thickness (mm)	U-Value W/(m^{2}K)	g- Value (%)	Application
1	Wacotech (“wacotech,” n.d.)	TIMax CA	Glass + Honeycomb(Cellulose triacetate) + Glass	28	2.2	65	Solar collectors, Skylights, Light domes
				48	1.5	63	
				68	1.3	62	
				88	1.0	59	
				108	0.8	56	
				128	0.6	53	
		TIMax GL/S	U-Glass + glassfiber/binder + U-glass	68	1.4	43	Double glazing systems – rooflights, membrane roofs and facades
		TIMax GL-PlusF	U-Glass + glassfiber/binder + U-glass	68	1.2	25	
		TIMax® GL System Ug 0,8	Glass + glassfiber/binder + glassfiber/binder + glass	160	0.79	19	Glass facades
2	Sto (“StoSolar: tot 95% rendement uit zonne-energie | Sto,” n.d.)	StoSolar	Absorber + Transparent capillary plate + Fibre mat + Rendering with transparent glass spheres	85	1.21	60	TI exterior thermal insulation composite system – Tiwall
				105	1.03	60	
				125	0.90	60	
				145	0.85	59	
3	OKALUX (“OKALUX GmbH,” n.d.)	OKAPANE (PMMA-capillary slab in honeycomb arrangement)	U-profile glass + air(56mm) +U-profile glass	70	1.8	59	Light diffusing insulating panels for U-shaped glass. daylighting purpose
			U-profile glass + glass fibre mat+ OKAPANE (40mm)+ glass fibre mat + air (16mm) +U-profile glass	70	0.9	36	
		KAPILUX-TWD	Toughened outer glass + KAPIPANE + inert gas(Krypton) + Toughened inner glass	49	0.7	61	Solar wall heating - Facade

S.No	Manufacturer	Product name	Material type/make-up	Thickness (mm)	U-Value $W/(m^2K)$	g- Value (%)	Application
		KAPILUX- T/-W/WS	Outer glass + inert gas(krypton) + middle glass + 2 KAPIPANE +inner glass	42	0.8	45	Insulating glass for daylighting purposes.
4	Lamberts glass (“Glasfabrik Lamberts GmbH & Co. KG: Lamberts Linit,” n.d.)	Lamberts LINIT – U profile glass	LINIT U-profile glass + OKAPANE (40mm) + air (16mm) +LINIT U-profile glass	70	0.9	36	Facades
5	LINIT UK (“Linit Insulation - Linit UK,” n.d.)	LINIT UK GL max	LINIT U-Glass + TIMax GL plus(glassfiber/binder) + LINIT U-glass	68	1.2	25	Rooflights, membrane roofs and facades
6	GLASSX (“GLASSX AG - Products,” n.d.)	GLASSX® crystal	Glass + Prism plate + inert gas +glass + inert gas + glass + PCM(phase change material) + glass	79	0.48	48	Translucent wall element – Used as facades for daylighting and thermal insulation
7	Gap Solution (“GAP: GAP Solutions GmbH,” n.d.)	GAP- Panel	ESG float glass + air gap + cardboard honeycomb + support plate	84	1.18	23	Façade system with prevention of overheating
8	Covestro (Communications, n.d.)	Makrolon® Multiwall UV 7M/50-28	Polycarbonate sheet with M-structure. 13 layers of the sheet with air space between.	50	0.84	39	Flat glazing applications –industrial glazing’s, partition walls, skylights, roofing, facades
9	Advanced glazings ltd (“Solera | Architectural Daylighting - AdvancedGlazings.com,” n.d.)	SOLERA®S & T	Exterior glass + light diffusing veil + transparent InsolCore® + light diffusing veil + Interior glass	76.2	1.14	9 - 51	Daylighting systems – standard curtain wall, storefront, window and skylight systems
10	Kalwall (“Home,” 2015)	Kalwall Translucent sandwiched panels	Interior FRP face sheet + Aluminium or thermally-broken grid core + Translucent insulation (Fiberglass ‘Batts’) + Exterior FRP face sheet	100	0.45	4	Facades – wall systems, unitised curtain walls. Skylights, sky roof
11	Wasco SkyLights (“Wasco Skylights for Commercial and Residential Daylighting,” n.d.)	Lumiwall – -Translucent Polycarbonate system	Multiwall polycarbonate sheet. 7 layers of the sheet with air space between	40	1.5	30	Translucent wall panel system

S.No	Manufacturer	Product name	Material type/make-up	Thickness (mm)	U-Value $W/(m^2K)$	g- Value (%)	Application
12	Reglit ("Reglit Glass Architecture / Pilkington Profilit U-Profiled Glass," n.d.)	Profiled glass insulation	Pilkington Profilit U glass + TIMax GL + TIMax GL + Pilkington Profilit U glass	160	0.85	19	Façade systems
13	CPI daylighting ("cpi daylighting," n.d.)	Pentaglas® 12	Polycarbonate sheet with 3 layers of nano-cells(honeycomb structure)	12	2.7	74	Daylighting systems -Wall systems, skylights
		Pentaglas® 16	Polycarbonate sheet with 5 layers of nano-cells	16	2.15	54	Daylighting systems -Wall systems, skylights
		UniQuad®	10mm Pentaglas translucent panel + air cavity/custom insulation + 10mm Pentaglas translucent panel	76 - 108	1.3 - 0.45	41 -8	Daylighting system – translucent building envelope solutions
14	Kingspan Limited ("Home - KIP Division - Kingspan Insulated Panels UK & Ire," n.d.)	Kingspan Architectural KS1000 DLAWP	Multiwall Polycarbonate sheet with M structure. 7 layers of the sheet with air space between.	38	1.3	58	Wall Light system- vertical and horizontal applications
15	Pilkington ("Pilkington Profilit™," n.d.)	Pilkington Profilit™ -U shaped profiled glass	Double shell glazing:- Exterior glass (Pilkington Profilit™) + cavity(air) + Interior glass (Pilkington Profilit™ plus 1.7)	60	1.8	63	Daylighting systems – Curtain walls, curved walls, Facades.
16	SABIC ("LEXAN™ THERMOCLEAR™ Sheet," n.d.)	LEXAN™ Thermoclear™ LT2UV55S	Multiwall polycarbonate sheet with X structure. 9 layers of the sheet with air space between.	55	0.90	52	Residential flat & curved glazing, roof glazing, Building facades and claddings

Appendix 2 – TI System manufacturers with aerogel

Table A. 2

S.No	Manufacturer – Consortium Member	Product example	Material type/make-up	Thickness (mm)	U-Value W/(m^{2}K)	g- Value (%)	Application
Aerogel TI manufacturers - Lumira® aerogel Consortium							
Structural polycarbonate panel							
1	AmeriLux International (“Lumira® aerogel enhances mutiwall polycarbonate systems insulation.,” n.d.)	Lumira® aerogel polycarbonate system	Lexan 3 wall polycarbonate panel filled with Lumira® aerogel.	25	0.90	54	Translucent insulating panels Used in daylighting systems
			Lexan Polycarbonate Thermoclick panel filled with Lumira® aerogel	40	0.56	42	
Daylighting systems using structural polycarbonate panel							
2	Bristolite® Daylighting Systems (“Bristolite Daylighting Systems,” n.d.)	Nano Insulgel/ Lumira skylights	Acrylic outer domes over 16mm Nano Insulgel/ Lumira® aerogel-filled Lexan multiwall polycarbonate panel	16	1.13	42	Skylight Dome
3	CrystaLite, Inc. (“Lumira Aerogel | CrystaLite, Inc.,” n.d.)	Lumira® aerogel polycarbonate system	Lexan Polycarbonate Thermoclick panel filled with Lumira® aerogel	40	0.56	42	Translucent insulating panels; Used in daylighting systems
4	Duo-Gard Industries (“High Performance Energy Management and Savings with Lumira® aerogel,” n.d.)	Lumira® aerogel polycarbonate system	Clear cellular polycarbonate sheet filled with Lumira® aerogel	40	0.51	42	Skylights, vertical daylighting systems
5	Solar Innovations, Inc. (“Lumira ® Aerogel,” n.d.)	Lumira® aerogel polycarbonate system	Multi-cell polycarbonate panel filled with Lumira® aerogel system	70	0.25	19	Curtain walls, skylights, pool enclosures, greenhouses, conservatories.
6	Wasco Skylights (“Daylighting Systems with Lumira Aerogel -	Lumira® aerogel polycarbonate system	Multiwall polycarbonate panel filled with aerogel	25	0.91	54	Used in the canopy, vault, structural, vertical and unit daylighting systems

S.No	Manufacturer – Consortium Member	Product example	Material type/make-up	Thickness (mm)	U-Value $W/(m^2K)$	g- Value (%)	Application
	Lightweight Polycarbonate Panel Skylights," n.d.)	EcoSky3™ E3CS	Acrylic outer domes over 10mm Lumira® aerogel-filled multiwall polycarbonate panel	10	1.42	34	Unit skylight
			Aerogel TI manufacturers				
7	Advanced Glazings Ltd ("Solera® + Aerogel R18 | Advanced Glazings," n.d.)	SOLERA® + Aerogel R18	Exterior glass + light diffusing veil + transparent InsolCore® filled with Lumira® aerogel + light diffusing veil + Interior glass	76.2	0.31	7-30	Curtain wall, Skylights
8	ALCAUD SAS ("Alcaud - sécurité incendie par le désenfumage naturel, de ventilation confort, de protection solaire et d'éclairage naturel," n.d.)	Lumigel	Lexan thermoclear multiwall polycarbonate filled with Lumira® aerogel	25	1.1	59	Vertical walls: industrial, sports, housing. Daylighting systems
9	Birdair ("Insulated Tensioned Membrane - Fabric Membranes | Birdair, Inc.," n.d.)	Tensotherm™	PTFE fibreglass fabric membrane exterior skin + Translucent blanket, embedded with aerogel (CABOT) + PTFE fibreglass acoustic or vapour barrier interior liner	24	0.56	2.3	Translucent and insulated tensile fabric roofing material
10	ECODIS ("ECODIS AEROTECH | Ecodis," n.d.)	ECODIS AeroTech ®	2x16mm AeroTech® AeroTech® - Lexan thermoclear multiwall polycarbonate filled with Lumira® aerogel.	32	0.73	N/A	It is used in skylights, Illumination vaults, canopies, translucent cladding.
11	ESSMANN GmBH ("ESSMANN | ESSMANN AeroTech," n.d.)	ESSMANN AeroTech ® – Same product as distributed by ECODIS	ESSMANN daylight panel SVPC ih – 8 wall Polycarbonate panel filled with ESSMANN AeroTech ® in all chambers	40	0.48	N/A	Façade system
12	GUNISIGI ("Günışığı Aydınlatma," n.d.)	NanoLUX®	Polycarbonate panel filled with Lumira® aerogel	70	0.25	19	Translucent walls, roof windows, smoke flue
13	Kalwall ("Thermal Performance," 2015)	Kalwall + Lumira® aerogel	Interior FRP face sheet + Aluminum or thermally-broken Grid Core+ Lumira® aerogel + Exterior FRP face sheet	70	0.284	25	Daylighting systems - Façades, skylight systems, skyroofs
14	Okalux ("OKAGEL," n.d.)	Okagel	4mm thick low iron outer pane + Lumira® aerogel + 6mm laminated low iron glass inner pane.	60	0.3	63	Light diffusing insulating glass for daylighting purposes.

S.No	Manufacturer – Consortium Member	Product example	Material type/make-up	Thickness (mm)	U-Value $W/(m^2K)$	g- Value (%)	Application
15	Roda (“info Lumira,” n.d.)	Roda Lumira® aerogel	Polycarbonate panel (Klick-Panel PC 560-10) filled with Lumira® aerogel	60	0.385	24	Daylighting systems – facades, continuous roof lights.
16	Skydome (“Aérogel Lumira - Skydôme provides natural lighting, ventilation and natural smoke evacuation systems,” n.d.)	Aerogel Lumira ™	Polycarbonate panel filled with Lumira® aerogel	16	1.31	59	Skylights, Windows, cladding and vault skydome
17	Technical glass products (“Pilkington Profilit with Lumira Aerogel | Insulated Channel Glass,” n.d.)	PILKINGTON PROFILIT™ with Lumira® aerogel	Lumira® aerogel encased in 25mm polycarbonate panel placed in between double glazed Pilkington profilit channel glass cavity	60	1.08	31	Daylighting systems
18	Xtralite Rooflights (“Structural Glazing Lumira,” n.d.)	Structural Glazing Lumira	Tripple walled polycarbonate panel filled with Lumira®	16	1.3	N/A	Rooflights and panel glazing’s
19	LINIT UK (“Linit Insulation - Linit UK,” n.d.)	Linit UK Aerogel	Aerogel filled in 16mm polycarbonate panel and placed between LINIT U channel glass	68	1.1	-	Daylighting systems
20	Scobalit AG (“Supramat Swiss - scoba®element / therm,” n.d.)	Scoba ® therm	Double skin composite made of glass fibre reinforced polyester filled with Lumira®aerogels	50	0.41	25	Daylighting panels for roof and walls
21	Brett Martin Daylight Systems(“News & Events | Lumira Aerogel | Brett Martin,” n.d.)	Lumira™ aerogel daylight glazing	25mm twinwall polycarbonate filled with Lumira aerogel	25	0.98	53	Glazing, roof lights, dome roof lights

Appendix 3 – Silica Aerogel manufacturers

Table A. 3

S.No	Manufacturer	Product name	Material type/make-up	Product features	Thermal conductivity W/(mK)	Application
1	CABOT corporation ("Home," n.d.)	Lumira® aerogel	Translucent silica aerogel – granular particles	Particle size – 0.7 -4.0mm, Light transmission 90%. U-value of 1.29 W/m^2K for 16 mm structural polycarbonate with Lumira aerogel	0.018	Daylighting systems
2	Nano High-Tech Co. Ltd, China ("Nano Tech Co., Ltd. - aerogel, aerogel blanket, insulation Panel, aerogel felt, thermal insulation," n.d.)	Nanuo – Daylighting panel (TP)	Translucent Silica aerogel particles, films and plate materials	FRP sheets and nano-silica aerogel -TP 70, have a thickness of 10mm with transmittance ≥ 70	0.025	Daylighting systems
3	Airglass AB ("Contacting Airglass," n.d.)	Airglass	Monolithic silica aerogels	Aerogel pane density – 50-200 kg/m^3 Size 60 x 60 x 2 cm^3	0.010	Aerogel glazing for super-insulating windows
4	Green Earth Aerogels Technologies (GEAT) ("Products of GEAT," n.d.)	GEAT SILICA AEROGEL AAA	Nanostructured material from rice husk and residues – Aerogel pellets	Amorphous silica Aerogel micro size particles with nano-sized bubbles. The thickness of particle – 56mm Thermal resistance – 1.019 (m^2 K)/W	0.056	Translucent wall, window or roof.
5	ENERSENS ("Enersens Aerogels | High Performance Silica Aerogel," n.d.)	Kwark® white	Silica aerogel particles	Translucent aerogel particles for filling translucent panels Particle size– Up to 3.5mm	0.018	Daylighting systems
6	JIOS Aerogel Corporation ("JIOS Aerogel » JIOS AeroVa® Aerogel Powder,"	JIOS AeroVa® Aerogel Powder	Silica aerogel powder	Primary product size is 1 to 20µm, but can be manufactured as per required demand. Blocks Ultraviolet rays below 300 nm, Infrared between 2700-	0.022	coating applications

	n.d.)			3200nm. Allows visible light transmission.		
7	Aerogel technologies. LLC (“Buy Aerogel Materials Online | Aerogel Technologies,” 2017)	Classic Silica™ aerogels	Monolithic silica aerogel	Available in variety of shape, size and density.	N/A	Demonstration and education purpose.
8	Guangdong Alison Hi-Tech Co.,Ltd. (“Alison Aerogel -- Guangdong Alison Hi-Tech Co.,Ltd.,” n.d.)	Alison Aerogel	Silica aerogel particles	Particle size – 0.1 ~ 5mm, Pore diameter - 20 ~ 100nm Excellent light diffusion and insulation properties	N/A	Wide range of insulation application

There are more silica aerogel manufacturers, but to author’s knowledge, some of them produce aerogels for opaque insulation thus not included in this table.

Appendix 4 – List of 86 research papers on TIM

Table A. 4

S.no	Year	Author	Paper	Application	Material	TI geometry
1	1928	V.B Veinberg	Results are reported in the book - Optics in Installations for utilisation of solar energy, published in 1959	Solar Desalination	Specially treated paper	Honeycomb
2	1963	G. Francia	A new collector of solar radiant energy—Theory and experimental verification	Linear Fresnel solar collector for the steam engine	Long glass tubes in the collector	Cellular Honeycomb
3	1965	K.G.T. Hollands	Honeycomb devices in flat plate collector	Flat-plate solar collectors	Assumption - Glass or some plastics	Honeycomb (Rectangular, square, triangular and hexagonal)
4	1968	P. Pellette, M. Cobble, P. Smith	Honeycomb thermal trap	Solar collector - without optical concentration	Glass reinforced plastic	Hexel honeycomb
5	1969	H.Tabor	Cellular Insulation(Honeycombs)	Solar collectors – (a.) Concentrating collectors, b.) FPC	For concentrating collectors material- glass and for FPC - plastic	Cellular honeycomb
6	1976	K.N. Marshall; R.K. Wedel; R.E. Dammann	Development of plastic honeycomb flat-plate solar collectors	High-performance FPC	Lexan, Mylar, Tedlar, and Kapton	Thin film hexagonal shaped honeycombs
7	1978	K.G.T. Hollands, K.N. Marshall, R.K. Wedel	An approximate equation for predicting the solar transmittance of transparent honeycombs	Transparent Honeycombs for solar energy applications	A theoretical model is compared with hexagonal-celled Lexan honeycomb	Square-cell honeycomb and approximately valid for hexagonal honeycombs
8	1982	J. G. Symons	The Solar Transmittance of Some Convection Suppression Devices for Solar Energy Applications: An Experimental Study	General Solar applications for Convection suppression device	FEP Teflon 1 film and Tubular Glass honeycomb	Honeycomb and various slat geometry
9	1983	Michael RUBIN and Carl M. LAMPERT	Transparent silica aerogels for window insulation	Window Insulation	Silica Aerogel	Quasi-Homogeneous
10	1984	W. Stahl, V. Wittwer, A. Pflüger	Transparent insulation	General Solar applications	1.) Parallel structure - PVF (Polyvinylfluoride) films and PVC (Polyvinylchloride),	Parallel, Perpendicular (honeycomb and

S.no	Year	Author	Paper	Application	Material	TI geometry
					2.) Perpendicular structure - (a) Thin Film Structure (TFS) of PETP (Polyethelenēterephtalate), (b) Capillary structure of PC(Polycarbonate), 3.) Homogeneous structure - Silica Aerogel	capillary), homogeneous.
11	1984	A. GOETZBERGER, J. SCHMID & V. WITTWER	Transparent Insulation System for Passive Solar Energy Utilization in Buildings	TI Buildings - TI wall for heating	PMMA foam,	Cavity(PMMA foam) and absorber-perpendicular (Capillaries)
12	1985	N.D. Kaushika, M.B. Banerjee	Thermal analysis of honeycomb solar pond	solar pond		Honeycomb
13	1987	A. GOETZBERGER	Potential uses of transparent insulation materials for thermal collectors and in buildings	1.) Windows 2.) Transparent insulation on walls (LECIS - Light Energy Converting Insulating System), 3.) Solar Collectors, 4.) Integrated Collector storage(solar pond)	1.) Acrylic Foam - expanded Polymethylmethacrylate, 2.) Honeycombs of plastic foil 3.) Aerogel	1.) Perpendicular - Honeycomb and Capillary, 2.) Cavity - Acrylic foam, 3.) Homogeneous - Aerogel
14	1987	Werner J. PLATZER	Solar transmission of transparent insulation material	General	1.) Polycarbonate (10cm thickness rectangular honeycomb), 2.) PMMA foam (Cavity Structure), 3.) Aerogel Pellets (Homogeneous)	1.) Absorber parallel, 2.) Absorber perpendicular - Honeycomb and capillary, 3.) Cavity - Foam, 4.) Homogeneous
15	1987	M.S. Sharma, N.D. Kaushika	Design and performance characteristics of honeycomb solar pond	Solar Pond		
16	1987	Antonio Pflüger	Minimum thermal conductivity of transparent insulation materials	General	1.) Aerogel pellets 2.) PMMA foam, 3.) Glass fibres, 4.) Capillaries 1.7 mm diameter, 5.) Hexagonal and waveform honeycombs, 6 mm diameter, 6.) Plastic tubes 10 mm diameter, 7.) Rhomboidal honeycomb 25 mm × 100 mm	All four geometries: honeycombs, plastic tube structures, PMMA foam, glass fibres, silica aerogel and others.
17	1991	N.D. Kaushika, R.Padma Priya	Solar transmittance of honeycomb and parallel slat arrays			1.) Square celled honeycomb 2.) Parallel slat arrays

S.no	Year	Author	Paper	Application	Material	TI geometry
18	1992 (a)	W.J. Platzer	Calculation procedure for collectors with a honeycomb cover of rectangular cross-section	General, Flat - plate solar collector	Experiments were done using Polycarbonate honeycomb	A theoretical model for Absorber perpendicular - Rectangular Honeycomb
19	1992 (b)	W.J. Platzer	Directional-hemispherical solar transmittance data for plastic honeycomb-type structures	General, FPC	Polymethylmethacrylate, Polycarbonate, Polyethersulfone, Polyethylene, Polytetrafluorethylene-derivative	Small-celled honeycomb - Capillary structure and square honeycomb
20	1992 (c)	W.J. Platzer	Total heat transport data for plastic honeycomb-type structures	General, FPC	Polymethylmethacrylate, Polycarbonate, Polyethersulfone, polyethylene, Polytetrafluorethylene-derivative	Small-celled honeycomb - Capillary structure and square honeycomb
21	1992	A. Nordgaard and W. A. Beckman	Modelling of Flat-plate collectors based on Monolithic silica aerogel	Flat-Plate Collectors	Monolithic Silica Aerogel	Homogeneous - Aerogel
22	1993	N.D. Kaushika, P.P. Sharma	Transparent honeycomb insulated solar thermal systems for energy conservation	Solar Pond, Integrated collector Storage(ground, concrete sand and common brick as storage)	Plastics - Lexan and acrylic	Absorber perpendicular -Square celled honeycomb
23	1994	Volker Wittwer	The use of transparent insulation materials and optical switching layers in window systems	Building applications - Windows, facade	Different types - aerogel	1.) Absorber parallel, 2.) Absorber perpendicular - Honeycomb and capillary, 3.) Cavity - Foam, 4.) Homogeneous
24	1996	Werner J. Platzer, A. Goetzberger	Recent Advances in Transparent Insulation Technology	General overview		
25	1996	P. Avanti, M. Arulanantham, N.D. Kaushika	Solar thermal analysis of transparent-honeycomb-insulated ground collector-storage system	Integrated collector Storage(ground, concrete/sand as storage)	Plastic-Lexan	Absorber perpendicular - Square Celled honeycomb
26	1997	A.G. Lien, A.G. Hestnes, Ø. Aschehoug	The use of transparent insulation in low energy dwellings in cold climates			

S.no	Year	Author	Paper	Application	Material	TI geometry
27	1997 (published as 1999)	N.D. Kaushika, K.S. Reddy	Thermal design and field experiment of transparent honeycomb insulated integrated-collector-storage solar water heater	Integrated-collector-storage solar water heater	Lexan - cellular array Supplied by ArEI Energy Ltd	Absorber perpendicular - honeycomb (cellular)
28	1998	Werner J Platzer	Advances and problems of Transparent Insulation in the market Professionalization and diversification	Overview		
29	1998	K Duer, S Svendsen	Monolithic silica aerogel in super insulating glazings	TI Buildings - Glazings	Monolithic silica aerogel	Quasi-homogeneous
30	1999	Volker Wittwer, Werner Platzer	Transparent thermal insulation materials and systems: state of the art and potential for the future	Overview		
31	2000	Hongxing Yang, Zuojin Zhu, John Burnett	Simulation of the behaviour of transparent insulation materials in buildings in northern China	Passive solar building: TI wall and window	AREL Israel - Polycarbonate, OKALUX - polycarbonate	Square Honeycomb, Capillary honeycomb
32	2001	G.L.A.M. Swinkels, P.J. Sonneveld, G.P.A. Bot	SE—Structures and Environment: Improvement of Greenhouse Insulation with Restricted Transmission Loss through Zigzag Covering Material	Greenhouse	Polycarbonate	Absorber-perpendicular
33	2001	P.B.L. Chaurasia, John Twidell	Collector cum storage solar water heaters with and without transparent insulation material	integrated-collector-storage solar water heater	Polycarbonate	Honeycomb
34	2001	N.M Nahar	Design, development and testing of a double reflector hot box solar cooker with a transparent insulation material	Solar cooker	Polycarbonate Capillaries	Honeycomb
35	2002	M Reim, A Beck, W Körner, R Petricevic, M Glora, M Weth, T Schliermann, J Fricke, Ch Schmidt, F.J Pötter,	Highly insulating aerogel glazing for solar energy usage	TI Buildings - glazing for wall systems, daylighting systems, facades	Granular silica aerogels sandwiched in PMMA with krypton as filling gas and low e -coated glass	Quasi-Homogeneous
36	2003	US patent - US 6594957 B1 -	Insulated greenhouse	Greenhouse		Absorber-perpendicular

S.no	Year	Author	Paper	Application	Material	TI geometry
		Douglas I. Milburn				
37	2003	A.H. Abdullah, H.Z. Abou-Ziyan, A.A. Ghoneim	Thermal performance of flat plate solar collector using various arrangements of compound honeycomb	FPC	Polycarbonate	Honeycomb
38	2003	N.D. Kaushika, K. Sumathy	Solar transparent insulation materials: a review	Review		
39	2004	US patent - US20040191485 A1	Plastic body having low thermal conductivity, high light transmission and a capacity for absorption in the near-infrared region US 20040191485 A1	General- TI building	Polymethyl methacrylate multiwall sheets	Cavity
40	2004	H. Suehrcke, D. Däldehög, J.A. Harris, R.W. Lowe	Heat transfer across corrugated sheets and honeycomb transparent insulation	Transparent Insulation	Cellulose acetate, acrylic	Absorber parallel - acrylic sheet, Absorber perpendicular - zigzag corrugated sheet and honeycomb made from cellulose acetate
41	2004	J.E.Y. Hum, K.G.T. Hollands, J.L. Wright	Analytical model for the thermal conductance of double-compound honeycomb transparent insulation, with validation	Transparent Insulation - Greenhouses	Polypropylene	Absorber Perpendicular - Honeycomb (circular cell)
42	2004	K.I. Jensen, J.M. Schultz, F.H. Kristiansen	Development of windows based on highly insulating aerogel glazings	TI building - aerogel glazing	Monolithic silica aerogel	Quasi-Homogeneous
43	2004	G.M. Wallner, R.W. Lang, H. Schobermayr, H. Hegedys, R. Hausner	Development and application demonstration of a novel polymer film based transparent insulation wall heating system	TI wall heating system - TI façade	Cellulose acetate films	Small-celled - absorber-perpendicular film,
44	2004	US patent - US 6699559 B1 - Douglas I. Milburn	Honeycomb transparent insulation with improved insulating ability	TI buildings and Greenhouses	polypropylene	Honeycomb
45	2005	A.A. Ghoneim	Performance optimisation of solar collector equipped with different arrangements of square-celled	Solar collector	Polycarbonate	Honeycomb

S.no	Year	Author	Paper	Application	Material	TI geometry
			honeycomb			
46	2005	US Patent - US6931796 B2	Extruded transparent/translucent sheet for roof structures	TI Building	Polycarbonate and a polymethyl methacrylate - multiwall sheets	Cavity
47	2005	G.M. Wallner, W. Platzer and R.W. Lang	Structure-property correlations of polymeric films; For transparent insulation wall applications. Part 1: Solar optical properties	Study on Transparent Insulation materials - polymer films Transparent Insulation Wall Applications	Maximum Operating temperature 100^0C - Cellulose acetate (CA), Cellulose triacetate (CTA), PMMA, PC, Copolycarbonate (CoPC), Polyethylene Terephthalate (PET), Polypropylene (PP), Poly(4-methyl-pentene-1), Maximum Operating temperature 150 to 200^0C - Polysulfone (PSU), Polyethersulfone(PES), polyaryl sulfone (PAS), Polyetherimide (PEI), Polyimide (PI), PEEK, E/TFE. F/EP, PFA	Small-celled, polymer film based absorber-perpendicular
48	2005	G.M. Wallner, W. Platzer and R.W. Lang	Structure-property correlations of polymeric films; For transparent insulation wall applications. Part 2: Infrared optical properties	Transparent insulation wall	same as part 1	Small-celled, polymer film based absorber-perpendicular
49	2005	G.M. Wallner and R.W. Lang	Ageing of polymeric films for transparent insulation wall applications	Transparent insulation wall	PMMA, PC films, polyethylene terephthalate (PET) and cellulose triacetate	small-celled, polymer film based absorber-perpendicular
50	2005	J.M. Schultz, K.I. Jensen, F.H. Kristiansen	Super-insulating aerogel glazing	TI building - aerogel glazing	Monolithic silica aerogel between the evacuated low iron glass	Quasi-Homogeneous
51	2005	M. Reim, W. Körner, J. Manara, S. Korder, M. Arduini-Schuster, H.-P. Ebert, J. Fricke	Silica aerogel granulate material for thermal insulation and daylighting	TI building - daylighting & evacuated Solar collector	Granular silica aerogel	Quasi-Homogeneous
52	2006	G.M. Wallner, R. Hausner, H. Hegedys, H. Schobermayr, R.W. Lang,	Application demonstration and performance of a cellulose triacetate polymer film based transparent insulation wall heating system	Transparent insulation wall TI facade system	Cellulose triacetate polymer film	Small-celled, polymer film based absorber-perpendicular
53	2007	I.L. Wong, P.C. Eames, R.S. Perera,	A review of transparent insulation systems and the evaluation of payback period for building applications	Review		
54	2007	K. S. Reddy	Thermal Modeling of PCM-Based Solar Integrated Collector Storage	Solar Integrated Collector Storage Water Heating		Absorber-perpendicular

S.no	Year	Author	Paper	Application	Material	TI geometry
			Water Heating System	System		
55	2007	A. Sridhar, K.S. Reddy,	Transient analysis of modified cuboid solar integrated-collector-storage system	Solar integrated-collector-storage system	Polycarbonate	Compound cellular array -absorber perpendicular
56	2008	J.M. Schultz, K.I. Jensen	Evacuated aerogel glazings	TI building - aerogel glazing	Monolithic silica aerogel between the glass	Quasi-Homogeneous
57	2011	Ruben Baetens, Bjørn Petter Jelle, Arild Gustavsen	Aerogel insulation for building applications: A state-of-the-art review	TI building -review	Silica aerogel	Quasi-Homogeneous
58	2011	Cinzia Buratti and Elisa Moretti	Lighting and Energetic characteristics of Transparent Insulating Materials: Experimental Data and Calculation	TI building - aerogel glazing	Monolithic silica aerogel, granular aerogel, Polycarbonate Capillary	Quasi-Homogeneous, Absorber-perpendicular
59	2011	Mark Dowson, David Harrison, Salmaan Craig and Zachary Gill	Improving the thermal performance of single-glazed windows using translucent granular aerogel	TI building - aerogel window(single glazed)	Granular silica aerogel	Quasi-Homogeneous
60	2011	Hamdi Kessentini, Roser Capdevila, Jesus Castro and Assensi Oliva	Numerical and Experimental study of flat plate solar collector with transparent insulation and overheating protection system	Solar collector - FPC with overheating protection system	Plastic TIM	Absorber-perpendicular (honeycomb)
61	2011	F. Giovannetti, M. Kirchner, G. Rockendorf, O. Kehl	Cellulose Triacetate honeycomb compounds for improved flat plate collector: Performance and reliability	Solar collector - FPC	Cellulose Triacetate	Absorber-perpendicular (honeycomb)
62	2011	Luis A. Alonso, Benito Lauret and Fernando Alonso	Free-Form, High Energy Performance, Transparent Envelope	TI Building - Façade system	(a)A natural cellulose fibre-reinforced epoxy resin matrix, with an outer gel coat coating to protect it from external agents; (b) a thermal/acoustical insulation component composed of a monolithic silica gel-filled vacuum chamber.	Can be termed as quasi-homogeneous
63	2012	By Luis Alonso, César Bedoya, Benito Lauret and Fernando Alonso	High Energy Performance with Transparent (Translucent) Envelopes	TI Building - Façade system	Same as above (62nd paper)	Can be termed as quasi-homogeneous

S.no	Year	Author	Paper	Application	Material	TI geometry
64	2012	Mark Dowson, Ian Pegg, David Harrison, Zahir Dehouche	Predicted and in situ performance of a solar air collector incorporating a translucent granular aerogel cover	Flat plate solar air collectors for buildings	Polycarbonate panels filled with Granular silica aerogel	Quasi-Homogeneous
65	2012	Cinzia Buratti and Elisa Moretti	Experimental performance evaluation of aerogel glazing systems	TI building - aerogel glazing	Monolithic and granular aerogel	Quasi-Homogeneous
66	2012	C. Buratti, E. Moretti	Glazing systems with silica aerogel for energy savings in buildings	TI building - aerogel glazing	Granular & monolithic silica aerogel	Quasi-Homogeneous
67	2012	US patent - US 8316598 B2	Translucent panel	TI- building	Multiwall Polycarbonate sheets	Cavity
68	2014	Ing Liang Wong, Philip Eames	A method for calculating the solar transmittance, absorptance and reflectance of a transparent insulation system	TI-systems for building façade application & general	6 mm outer glass pane, a 22 mm wide polymethylmethacrylate (PMMA) capillary cell section and an 8 mm inner glass pane	Absorber-perpendicular
69	2014	Tao Gao, Bjørn Petter Jelle, Takeshi Ihara, Arild Gustavsen	Insulating glazing units with silica aerogel granules: The impact of particle size	TI Buildings - Glazing	Granular silica aerogel	Quasi-homogeneous
70	2014	Jian Qu, Jianrong Song, Jie Qin, Zhongnan Song, Weidong Zhang, Yunxing Shi, Tao Zhang, Hongqiang Zhang, Rongpu Zhang, Zhongyu He, Xiao Xue	Transparent thermal insulation coatings for energy-efficient glass windows and curtain walls	TI buildings	Silicone-based, transparent heat insulation coatings	
71	2014	Mark Dowson, David Harrison & Zahir Dehouche	Trombe walls with nanoporous aerogel insulation applied to UK housing refurbishments	TI building - Trombe walls	Granular silica aerogel	Quasi-Homogeneous
72	2014	Hamdi Kessentini, Jesus Castro, Roser Capdevila, Assensi Oliva	Development of flat plate collector with plastic transparent insulation and low-cost overheating protection system	Solar collector - FPC and low cost overheating protection system	Cellulose triacetate film	Absorber-perpendicular (honeycomb)
73	2014	Franco Cotana, Anna Laura Pisello, Elisa Moretti, Cinzia Buratti	Multipurpose characterisation of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and	TI Buildings - Aerogel Glazing	Granular silica aerogel	Quasi-Homogeneous

S.no	Year	Author	Paper	Application	Material	TI geometry
			acoustic performance			
74	2014	Elisa Moretti, Michele Zinzi, Elisa Belloni	Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance	TI Buildings	Multiwall Polycarbonate panels	Cavity
75	2015	Masayoshi Fuji, Chika Takai, Hideo Watanabe, Kyoichi Fujimoto	Improved transparent thermal insulation using nano-spaces	General applications	Hollow silica nanoparticles (HSNPs) dispersed in polyurethane (PU)	Quasi-Homogeneous
76	2015	Yu Huang, Jian-lei Niu	Application of super-insulating translucent silica aerogel glazing system on commercial building envelope of humid subtropical climates – Impact on space cooling load	TI Buildings	Granular silica aerogel	Quasi-Homogeneous
77	2015	Takeshi Ihara, Steinar Grynning, Tao Gao, Arild Gustavsen, Bjørn Petter Jelle	Impact of convection on thermal performance of aerogel granulate glazing systems	TI Buildings - Glazing	Granular silica aerogel	Quasi-Homogeneous
78	2015	Esra Kucukpinara, Oliver Miesbauer, Yoash Carmi, Marc Fricke, Leif Gullberg, Can Erkey, Roland Caps, Malcolm Rochefort, Araceli Galvez Moreno, Clara Delgado, Michael Koehl, Paul Holdsworth, Klaus Noller	Development of Transparent and Opaque Vacuum Insulation Panels for Energy Efficient Buildings	TI Buildings	VIP core material - nano-monolithic composites of inorganic silica aerogels - [PDMS(OH)-silica aerogel composites] VIP Envelopes - LDPE sealing film + adhesive+PET substrate + Silicon oxide + ORMOCER + silicon oxide + adhesive + Silicon oxide + ORMOCER + silicon oxide + PET substrate	Quasi-Homogeneous
79	2015	Umberto Berardi,	The development of a monolithic aerogel glazed window for an energy retrofitting project	TI Buildings - Glazing	Monolithic Silica Aerogel	Quasi-Homogeneous
80	2015	C. Garnier, T. Muneer, L. McCauley	Super insulated aerogel windows: Impact on daylighting and thermal performance	TI buildings - Aerogel window	Granular silica aerogel	Quasi-Homogeneous
81	2016	Qilin Cai, Hong Ye, Qizhao Lin	Analysis of the optical and thermal properties of transparent insulating materials containing gas bubbles	Analysis of TIM properties	Glass/PC containing gas bubbles	Quasi-Homogeneous
82	2016	Muhammad Abdul Mujeebu, Noman Ashraf, Abdulkarim H.	Effect of nano vacuum insulation panel and nanogel glazing on the	TI Buildings - Glazing	Silica Aerogel	Quasi-Homogeneous

S.no	Year	Author	Paper	Application	Material	TI geometry
		Alsuwayigh	energy performance of office building			
83	2016	Yanyi Sun, Yupeng Wu, Robin Wilson, Sixu Lu	Experimental measurement and numerical simulation of the thermal performance of a double glazing system with an interstitial Venetian blind	TI Building - daylighting	Glass glazing with aluminium slats	Absorber-perpendicular
84	2016	Yanyi Sun, Yupeng Wu, Robin Wilson, Shuyue Sun	Thermal evaluation of a double glazing façade system with integrated Parallel Slat Transparent Insulation Material (PS-TIM)	TI Building - daylighting	Various thermal conductivity materials	Absorber-perpendicular
85	2017	Yanyi Sun, Yupeng Wu, Robin Wilson	Analysis of the daylight performance of a glazing system with Parallel Slat Transparent Insulation Material (PS-TIM)	TI Building - daylighting	Various thermal conductivity materials	Absorber-perpendicular
86	2017	Cinzia Buratti, Elisa Moretti, and Michele Zinzi	High Energy-Efficient Windows with Silica Aerogel for Building Refurbishment: Experimental Characterization and Preliminary Simulations in Different Climate Conditions	TI Buildings - energy efficient windows	Granular silica aerogel	Quasi-Homogeneous